Color and Colorimetry
Multidisciplinary Contributions

Vol. XIX A

Edited by Filippo Cherubini and Andrea Siniscalco

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Introduction

The GdC - Associazione Italiana Colore organizes the Color Conference every year, and it reached its nineteenth edition in 2024.
The two-day international event featured three keynote speakers: Phil Green (University of Science and Technology, Gjøvik, NO), Vien Cheung (University of Leeds, UK) and Robin Kingsburgh (York University Toronto, CA).
During the conference, the "Color Award / Premio Colore 2024" was also conferred, which went to the extraordinary painter Valerio Adami.
A special thanks go to the Color Award Commission, in the person of Cristian Bonanomi, Lia Luzzatto, and Lisa Vergelli (author of the winner's presentation text), for their valuable contribution.
Heartfelt thanks to Filippo Cherubini (IFAC-CNR) for his valuable help in managing the conference and to all the session chairs who moderated the speeches: Luca Cogo (Università degli studi di Milano Bicocca), Marcello Picollo (IFAC-CNR), Francesca Fragliasso (Università degli studi di Napoli Federico II), Ingrid Calvo Ivanovic (Universidad de Chile), Alice Plutino (University of Amsterdam), Verena M. Schindler (AIC Study Group on Environmental Colour Design), Alessandro Rizzi (Università degli studi di Milano Statale), Lisa Vergelli (Sapienza Università di Roma), Beatrice Sarti (Università degli studi di Milano Statale).
Thanks also to all the people who contributed to the conference's digital moderation and ensured its success: Paola Bertoletti, Alessandro Bortolotti, Gianluca Guarini, Ivanka Dicheva, Plutino Alice, and Vergelli Lisa.
Final thanks to Konica Minolta, which generously sponsored the conference.

Enjoy the reading.

Andrea Siniscalco
December 2024

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Color in Measurement - Color in Digital

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Modeling individual differences in color appearance through images' correction

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Paper 28

Extended Abstract

While perception is often assumed to be universal, significant individual variations shape our visual experiences. These differences influence every aspect of sensory processing, from basic sensitivity to high-level interpretations and conscious awareness. Even among observers with normal color vision, variations are pronounced, affecting everything from the eye's optics to subjective color perception. Consequently, two people viewing the same stimulus may perceive vastly different colors. There is growing interest to develop procedures for display calibration that correct for individual differences in the chromatic sensitivity of the observer. A focus of this effort has been on developing algorithms that account for individual differences in spectral sensitivity and color matching. Differences at this level are important for addressing variations in color discrimination and interobserver metamerism, and depend on factors of variability like the cones ratio, the macular and lens density and the receptors' peak. These differences impact modern wide-gamut displays.
However, there are also large individual differences in color appearance, or in the actual perception of the chromatic stimuli (i.e., how the color is seen by a specific observer), which are not predicted or corrected by differences in spectral sensitivity but have a potentially larger impact on how individuals experience large (suprathreshold) color differences. We describe a new technique for efficiently characterizing color appearance differences in real observers applied then to the correction of color images.
In our design, we first used a Minimum Motion Task, based on apparent motion driven luminance in chromatic gratings, to assess differences in luminance sensitivity, defining when chromatic stimuli are equiluminant. Correction factors were calculated to adjust the luminance of all the stimuli so that they were equated for each individual observer. In the following step, we measured the individual hue percepts of eight hues (the four unique hues – red, green, blue and yellow – and the four binary hues – orange, purple, blue-yellow and green-blue) of 21 color-normal observers.
Hue percepts can be measured with a simple identification task where observers had to pick the focal color of the tested hues. Each hue was measured six times in two sessions for a total of 12 measurements. Chromaticities covered the Derrington-Krauskopf-Lennie (DKL) color space (Figure 1b), from 0° to 360°, with a contrast of 80 and luminance of 20 cd/m^2. These measured differences in hue percepts were greater than the residual hue variation predicted by sensitivity differences (Figure 1a); we used them in our algorithm to correct color images and match hue percepts across observers. In a first step, the chromaticity of each pixel (RGB) was converted to the hue perceptual value for a standard (average) observer, and then this hue was mapped back to the chromaticity that would elicit the same perceptual response in an individual observer. With this correction, different observers – each looking at their own calibrated image – should more closely agree on the perceived image colors because they would have a similar color experience (Figure 2). Inspection of these images reveals conspicuous differences for a single observer, illustrating the broad spectrum of color perceptions that can arise from a single stimulus. Nevertheless, when observers view their personalized, corrected images, their perceived hues should converge: adjustments of this kind could thus lead to greater consistency in color appearance and image interpretation across individuals. Moreover, they could be easily implemented on standard displays to assure color constancy across devices because they require only measures of hue percepts and not spectral sensitivity. We are

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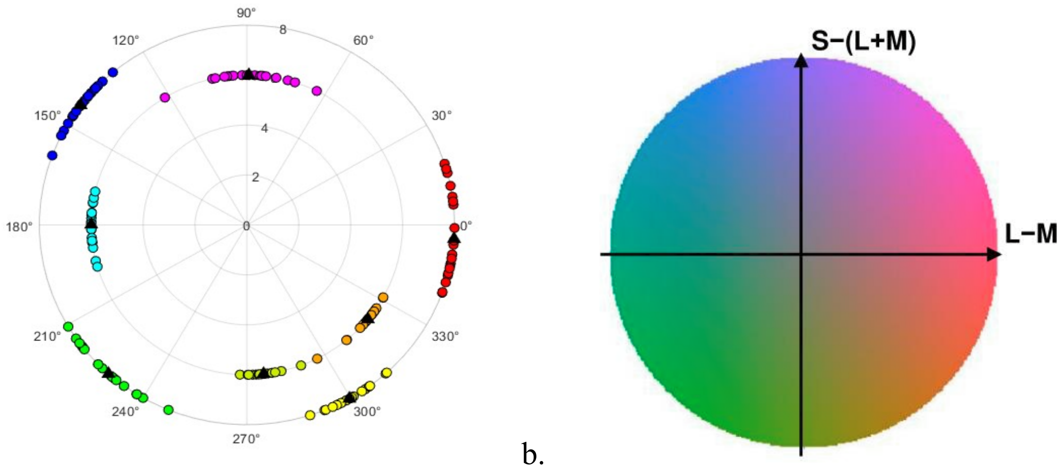
currently considering additional potential benefits and limitations of this approach and how we can ameliorate it.

Keywords: Individual differences, Color Perception, Spectral Sensitivities, Modeling, Color Calibration, Images Correction



a. b.

Fig. 1 – a) Individual differences in the settings for the eight hues tested, reported in the cone-opponent plane. Each circle is an individual observer's focal color for each hue, corresponding to the average of the 12 measurements; black triangles are to the standard observer's focal colors, made by the average of all the observers. | b) Derrington-Krauskopf-Lennie (DKL) color space, based on cone-opponent mechanisms (LvsM and SvsLM).

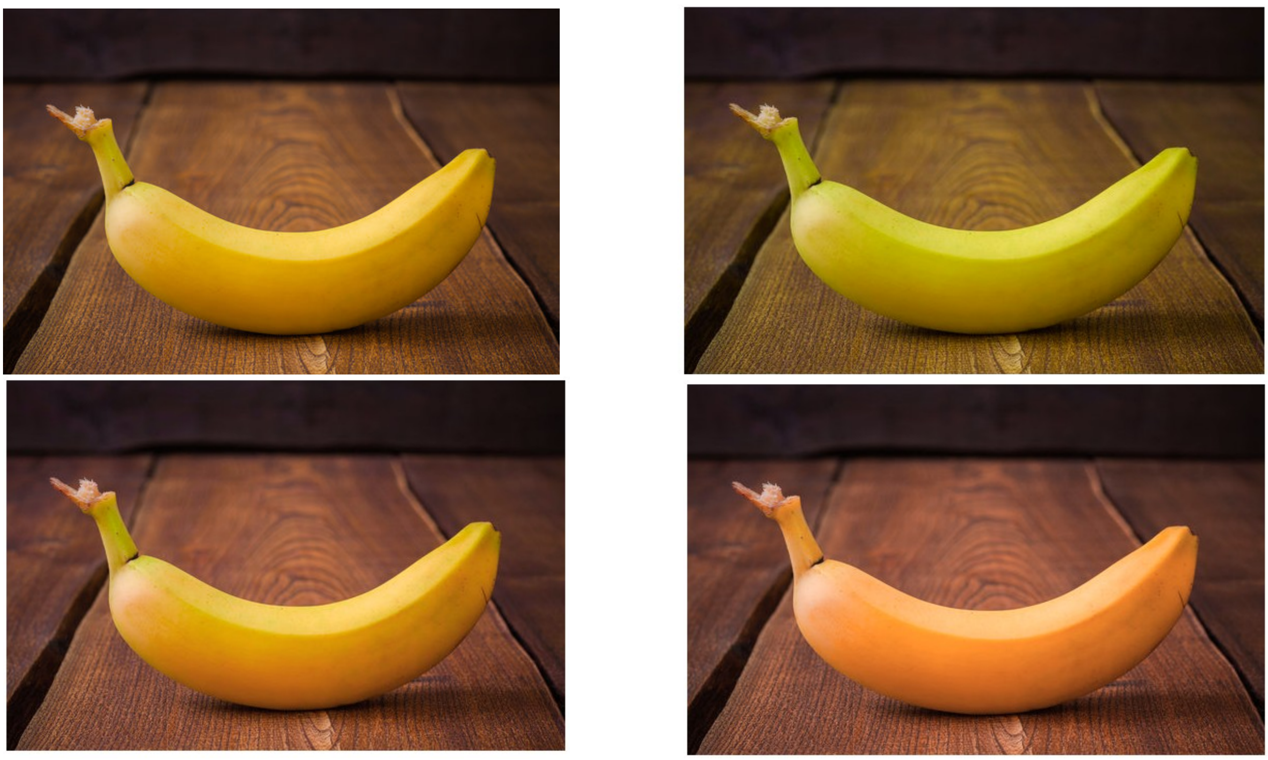


Fig. 2 - An example of the algorithm application. Top left image is the original image (Reference Image) and the three others are examples of adjusted images for the individual hue percepts of three different observers.

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Beware: M. E. Chevreul's chromatic circle may conceal multiple systems

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Abstract

M. E. Chevreul's chromatic circles are nowadays considered to be a reference colour space but different editions from 1855, 1861, 1864 and several copies per edition are available. The aim of this colorimetric study, enhanced by material analyses, was to review the variability of the chromatic circle's visual appearance within each edition and print run (i.e. a total of six copies). The results reveal that the visual appearance of these circles can vary within the same edition. The actions of the printer, changes in materials, in the paper support and different state of degradation of the inks are some of the factors that may have influenced the current colour of these coloured spaces.

Keywords: Graphic arts, Reference colour spaces, Colorimetric analysis, 19th century printing.

Introduction

Michel-Eugène Chevreul (1786-1889) is one of the major figures of the colour revolution that spread through the 19th century (Gage, 1993; Kuehni and Schwarz, 2008). Head of the Gobelin's manufacture, he designed several chromatic circles to classify colours and illustrate his law of contrast (Chevreul, 1839). Thus, M. E. Chevreul wanted to propose a universal colour space. This tool was subsequently reproduced and used for several decades by manufacturers, scientists, artists and designers, among others. A publication of these chromatic circles happened in successive editions in 1855, 1861 and 1864, using a process known as the "chromocalcography" (Chevreul, 1864). It raises nowadays the question of the reproducibility of the circle's visual appearance within each edition and print run. Changes in materials during printing batches (Korenberg *et al.*, 2019), as well as different advances in the state of preservation, are all factors that can influence the current visual appearance (Edwards and Villafana, 2020). This study complements previous research conducted on the material and colorimetric comparison between different editions (Malmert *et al.*, 2024). The corpus was expanded to include two copies of the 1st chromatic circle per edition, i.e. a total of six chromatic circles. They were subjected to systematic colorimetric analysis to study the variability in representation between two copies of the same edition, and the consequences of pigment degradation on their visual appearance.

Description of the corpus

The corpus is composed of two copies of each edition of M. E. Chevreul's 1st chromatic circle (Fig. 1). A total of six circles spread over four different conservation sites was thus analysed. Three of them are part of the rare books reserve of the Bibliothèque nationale de France (BnF), one comes from their department art and literature, one is kept in the library of the Muséum national d'Histoire naturelle (MNHN) and the last one, is part of the P. Signac Archives. Their localisation, as well as information available about printers and engravers are summarized in the Table 1. A supplementary description of the three editions from 1855 (Chevreul, 1855), 1861 (Chevreul, 1861) and 1864 (Chevreul, 1864) is given in the publication on the material and colour inter-editions comparison (Malmert *et al.*, 2024).

An initial comparison based solely on the legends accompanying these 1st chromatic circles enables their classification into three different groups:

- Group 1: the circle from 1855, BnF art et literature department (1855a) and the two circles from 1861 and 1864 in the BnF rare books reserve (1861b and 1864b) have the following legend: "Engraved and printed in colours by Digeon Patent of S.M. l'Impératrice -Galande 65 Paris" under the outline of the circle and in capital letters "Accepted at the exhibition from 1855" (Fig. 2a).
- Group 2: the circle from 1861, P. Signac Archives (1861a) and from 1855, BnF rare books reserve (1855b) have no legend (Fig. 2b).
- Group 3: the circle from 1864, held at the MNHN (1864a), has an insert with the words "Digeon Sc." on the right, "Published by J.B. Baillière and sons in Paris" in the middle and "Lamoureux imp." on the left (Fig. 2c).

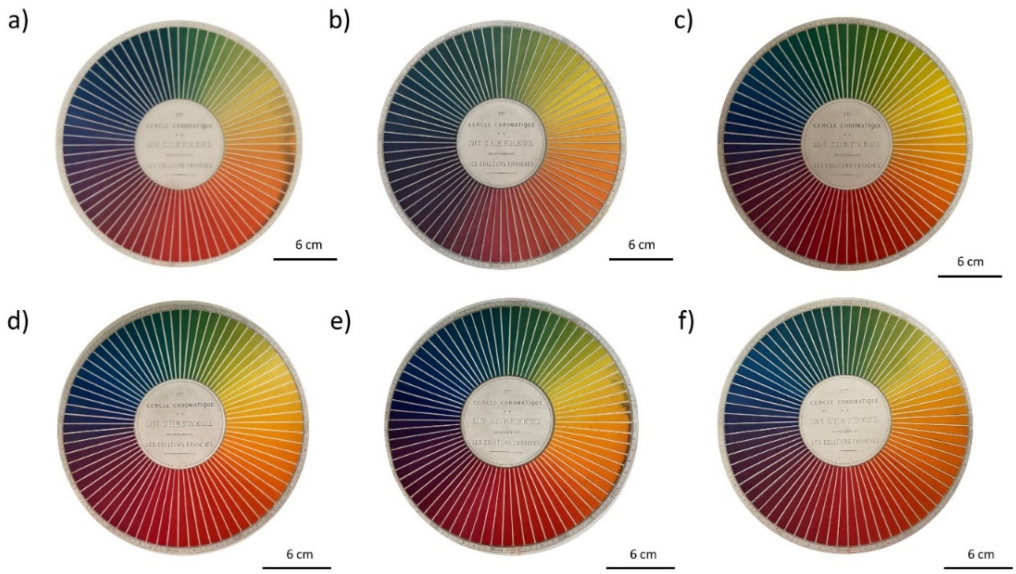

Fig. 1 - RGB images of the six different versions of M. E. Chevreul's 1st chromatic circle: a) 1855a, b) 1861a, c) 1864a, d) 1855b, e) 1861b, and f) 1864b.

	Sample name	Localisation	Accession number	Printer of the colour plate	Engraver of the colour plate	Printer of the book
1st copy from 1855* Fig. 1a	1855a	BnF, art and literature department	V-4527	R.-H. Digeon, n°65 Galande street	R.-H. Digeon, n°65 Galande street	E. Thunot et C°, 26 Racine street
2nd copy from 1855 Fig. 1d	1855b	BnF, rare books reserve	V-4527	R.-H. Digeon, n°65 Galande street	R.-H. Digeon, n°65 Galande street	E. Thunot et C°, 26 Racine street
1st copy from 1861* Fig. 1b	1861a	P. Signac Archives	-	R.-H. Digeon, n°65 Galande street	R.-H. Digeon, n°65 Galande street	Typography of Firmin Didot Brothers and sons, printers of the Institut, 56, Jacob street
2nd copy from 1861 Fig. 1e	1861b	BnF, rare books reserve	V-4528	R.-H. Digeon, n°65 Galande street	R.-H. Digeon, n°65 Galande street	Typography of Firmin Didot Brothers and sons, printers of the Institut, 56, Jacob street
1st copy from 1864* Fig. 1c	1864a	MNHN	Fol Res 56	Lamoureux imp.	Digeon sc.	J. B. Baillière and sons. Booksellers of the imperial academy of medicine,

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						19 Hautefeuille street
2nd copy from 1864 Fig. 1f	1864b	BnF, rare books reserve	V-4529	R.-H. Digeon, n°65 Galande street	R.-H. Digeon, n°65 Galande street	J. B. Baillière and sons. Booksellers of the imperial academy of medicine, 19 Hautefeuille street

Table 1 - Summary of information available on the title page, regarding the printer-engraver of the six circles. *Indicate the three copies analysed in the previous publication (Malmert et al., 2024).

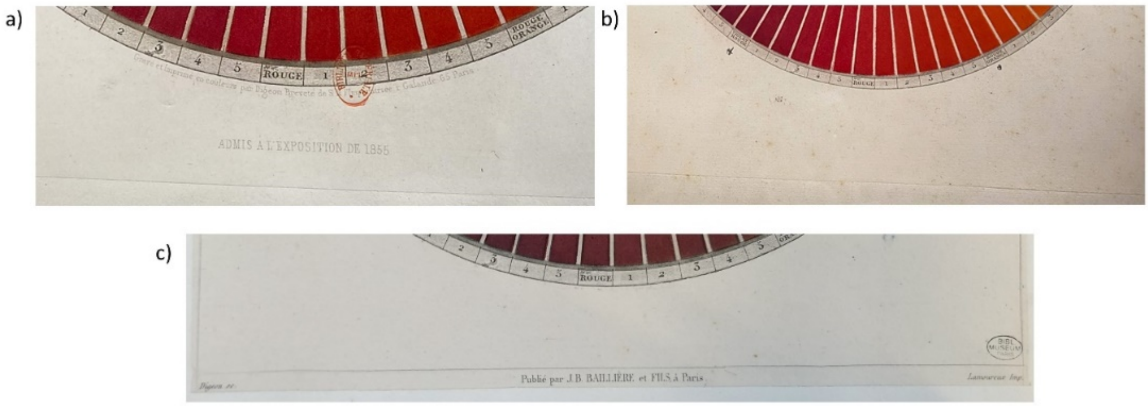

Fig. 2 - RGB images of the three different legends accompanying these colour plates: a) legend of the circle 1861b, belonging to group 1, b) no legend under the circle 1855b (group 2) and c) the footer under the circle 1864a (group 3).

Acquisition of hyperspectral reflectance data

The hyperspectral camera employed in this study is a handheld pushbroom Specim IQ commercialized by Specim® (Oulu, Finland), covering a spectral range in the visible and near-infrared (VNIR) from 400 to 1000 nm with 204 bands wavelength channels (spectral sampling of 3 nm and spectral resolution of 7 nm). The setup is reproduced as identically as possible for each copy book, according to the recommendations of the CIE (Internationale Beleuchtungskommission, 2004). The illumination is provided by two halogen lamps of 20 W placed on either side of the camera with a 45° incidence angle. The books stand on a 45° inclined surface. The camera is mounted on a tripod and a rotary head, so as to be perpendicular to the surface of the colour plates and at a distance of around 30 cm from them. The normalisation is ensured using a white Spectralon® standard.

Material identification methodology

Each hyperspectral datacube is analysed using the software SpectrononPro® (Resonon Inc, Bozeman MT, USA). An average reflectance spectrum of 6 × 6 pixels for each of the 72 hues per chromatic circle and 16 pixels for the orange degraded parts is extracted, then smoothed using a Savitsky-Golay filter (15 number of points, 2 polynomial degree). One copy of each edition (1855a, 1861a and 1864a) is also subjected to further material analysis using XRF, Raman and mid-infrared spectroscopy (Malmert *et al.*, 2024).

Extraction of colorimetric data

The conversion of the visible average reflectance spectra into CIE-LAB coordinates is achieved using the plug-in CIE colour-space conversion from SpectrononPro®. Reflectance scale factor is set to 1, the illuminant to D65 and the standard observer to 10°. An average (6 × 6 pixels) and a standard deviation of L* a* and b* values are calculated for each of the 72 hues with the help of a homemade MATLAB code. In a second step, chromaticity diagrams are plotted.

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Each dots is represented with RGB values calculated from the L*, a* and b* coordinates thanks to the matlab function "labtorgb" (*Convert CIE 1976 L*a*b* to RGB - MATLAB lab2rgb - MathWorks France*, R2024a). The ΔE_{00} colour difference is calculated between two successive hues within the same circle and between two identical hues from two different book copies with a homemade MATLAB code using the function "ΔE00" (Sharma, Wu and Dalal, 2005).

Determination of the reproducibility error for colorimetric measurements

The main challenge of the colorimetric survey is the repeatability and reproducibility of measurement, which depend largely on the illumination and the location of the camera (Lorusso, Natali and Matteucci, 2007; Signoroni *et al.*, 2020; Cherubini *et al.*, 2023). This issue is particularly relevant for our corpus, which consists of six circles scattered over four different sites, requiring as many different configurations to adapt to their environment and exhibition constraint. The robustness of our colorimetric measurements and the processing of the data is tested by carrying out two acquisitions, two different days on the same chromatic circle. The colour difference between the two acquisitions is calculated for each of the 72 hues of the 1855a (Fig. 3a) and 1864a (Fig. 3b) circles. The standard deviation of these ΔE_{00} is highlighted by a grey band on both graphs. The ΔE_{00} of the 1855a range from 0.1 to 3.7, while those of 1864a range from 0.6 to 5.7. These higher ΔE_{00} values are observed for both green and red hues (Fig. 3b), which may be explained by a more pronounced difference in the vertical tilt of the colour plates during acquisition. The inclination of the camera, its distance from the coloured plate and the lighting are all parameters that can affect the reproducibility of our acquisitions. Therefore, considering the maximum error associated to our experimental conditions, a minimum ΔE_{00} of 5 will be set as the threshold value above which two colours are similar, in the rest of this study.

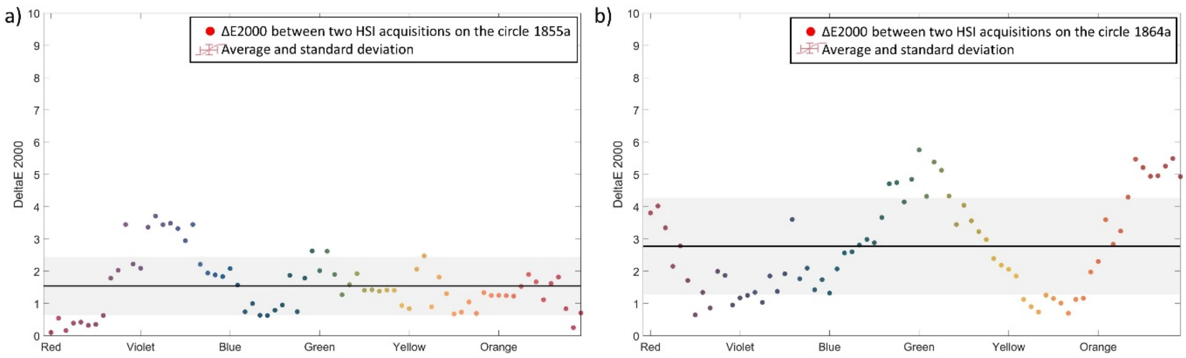

Fig. 3 - ΔE_{00} of each of the 72 hues, calculated between two hyperspectral data cubes of the circle a) 1855a and b) 1864a, acquired on two different days.

Material study of the corpus

The multi-modal analyses (XRF, Raman, mid-infrared spectroscopy and visible hyperpsectral imaging) carried out on one copy of each edition (1855a, 1861a and 1864a), allowed the identification of the chemical composition of the four inks used to print the 72 hues of the circles (blue, orange, red and yellow) (Malmert *et al.*, 2024). Visible reflectance spectra confirmed these results for the second copies analysed (1855b, 1861b and 1864b). The red ink is composed of cochineal lake, whereas, the orange ink contains minium. The chrome yellow ink has different Cr and S ratios, depending the edition: the circles 1855a, 1861a, 1855b, 1861b are of the form $PbCr_{0.4}S_{0.6}O_4$, 1864a has the form $PbCr_{0.7}S_{0.3}O_4$ and 1864b remains undefined. Finally, the blue ink of all the copies contains a single blue pigment: Prussian blue, except for the 1864a version that contains a mixture of Prussian blue and Scheele or Emerald green, identified by XRF and VNIR spectroscopy.

These results show that, from a purely material point of view, the copy from 1864a differs from all the others in the composition of its blue and yellow inks

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Colorimetric comparison of the corpus

The chromaticity diagrams of the two copies from 1864, belonging to the group 1 (1864b) and 3 (1864a), are compared in the

Fig. 4a. The ΔE_{00} values calculated for each of the 72 hues in the two copies are particularly high. 19 of the 72 hues exceed the ΔE_{00} threshold of 5 previously set, meaning that the difference in hue is not negligible to the naked eye (

Fig. 4c). The colour differences are particularly marked on the violet-blue and yellow-orange sections, with ΔE_{00} values above 10. These observations corroborate the differences in the materials highlighted in the previous section. The presence of copper arsenate in the blue ink change its colour and impact the hues in which this ink is printed, such as they appear less blue and a little more greenish. The differences in the yellow-orange hues can be explained by variation of the Cr/S ratio, since the less sulphur there is, the more orange the hues (Matias Otero, 2018). The circle 1864a owned the higher ratio of Cr ($PbCr_{0.7}S_{0.3}O_4$) and the presence of a supplementary baryte filler, lighten the yellow hue (Malmert *et al.*, 2024).
A second comparison is made between two circles from different editions (1855b and 1861a) but belonging to the same group defined in the description of the corpus, i.e. the group 2 'without legend' (

Fig. 4b). These circles show lower differences in colour than those observed in the 1864 intra-edition comparison. An average ΔE_{00} of 5 is obtained over the 72 hues (

Fig. 4d), the threshold previously set for identical hues, showing minor discrepancy in hue.
The colour difference between two successive hues on the chromatic circle also provides information about the printing of these circles. Two neighbouring hues should have a small

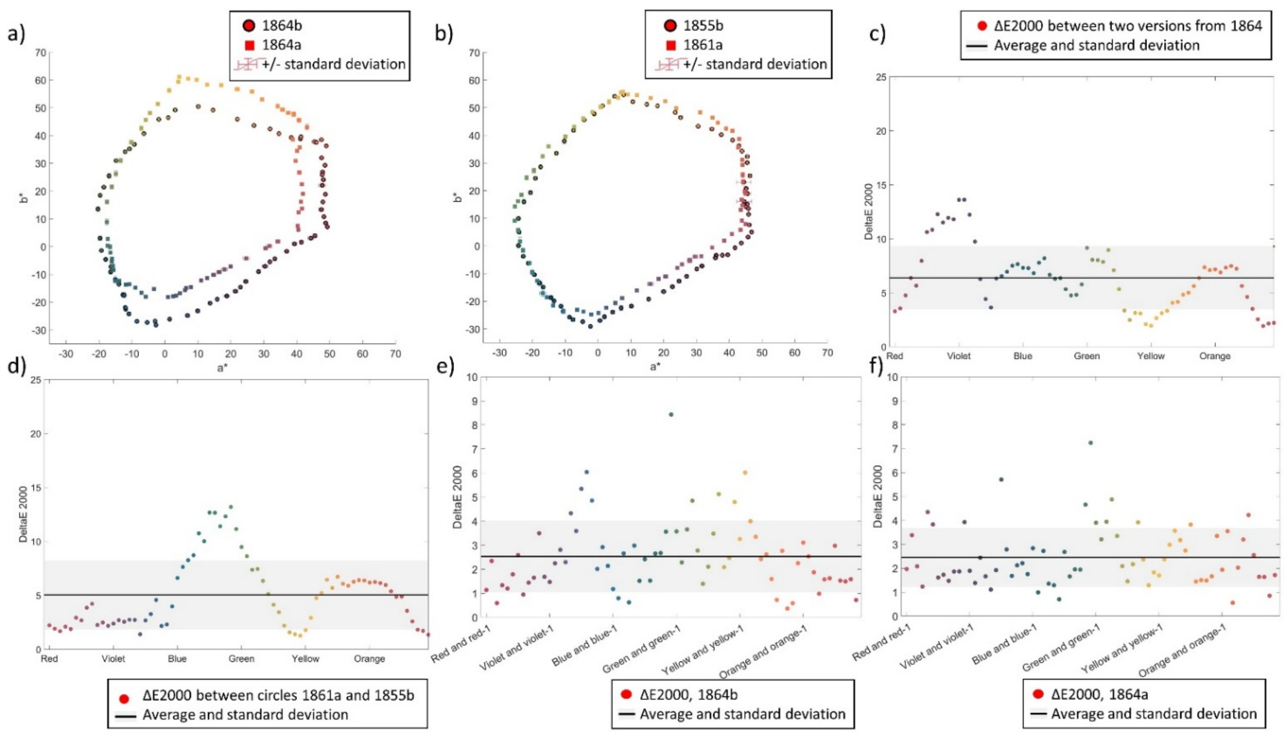

Fig. 4 - Comparison of the chromaticity diagram a*b* of two copies a) from 1864 (from group 1 and 3) and b) from 1855b and 1861a, belonging to the same group 2. The respective ΔE_{00}, calculated between each of the 72 hues of the

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two copies are represented in c) 1864a and 1864b and in d) 1861a and 1855b. ΔE_{00} between two successive hues on the circle are calculated for chromatic circles e) 1864b and f) 1864a

colour difference, allowing the viewer to move seamlessly from one to the other. The challenge is not to obtain ΔE_{00} values that are too high, which would create a visual break, or too low, since the difference in colour between two neighbouring colours must still be perceptible, *i.e.* $\Delta E_{00} > 1.5$ (Beltran *et al.*, 2021). The calculation of these ΔE_{00} on the three circles 1855a, 1861b and 1864b, belonging to the group 1, shows very similar results. For example, the average of the 71 ΔE_{00} from the circle 1864b is 2.5 and the standard deviation: 1.5 (

Fig. 4e). The unique circle 1864a, in terms of its material composition, has a lower mean ΔE_{00} of 2.4 with a smaller standard deviation of 1.2 (

Fig. 4f). This shows that the ΔE_{00} are less dispersed than in the other examples and reflects a better transition between two neighbouring hues, such as this latest version also seems to be the best executed

State of degradation

Of all the circles studied, only circles 1855a and 1861b show visible signs of degradation in the orange-yellow hues, resulting in localised blackening of the top layer of orange ink (Fig. 1a and e). The contrast between the degraded and non-degraded part can be seen by choosing a wavelength of 640 nm (Fig. 5a), since in the visible spectrum, this degradation leads to a drastic reduction in the reflectance from 570 nm to 1003 nm (Fig. 5b). The degradation of minium into galena, discussed in the previous publication (Malmert *et al.*, 2024), would probably be favoured by the presence of sulphur in the yellow ink ($PbCr_{0.4}S_{0.6}O_4$). On the circle 1861b, this blackening from the hues *yellow* to *orange-yellow-5* results in a significant loss of luminosity L* and a reduction in the proportion of yellow, visible by a shift of the b* coordinates towards zero in the degraded areas (Fig. 5c). On these hues, several ΔE_{00} values of over 22 are obtained, confirming the observations made with the naked eye and the radical change in colour of these degraded areas.

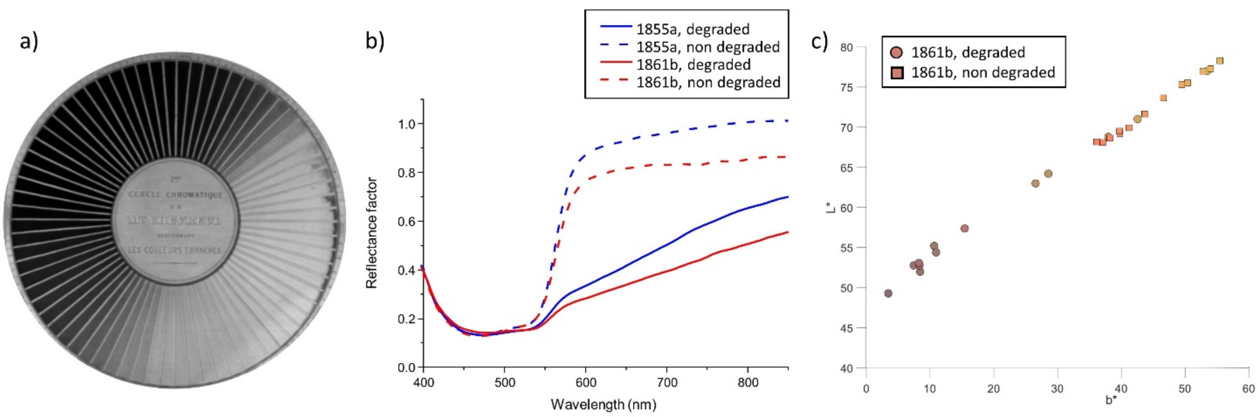

Fig. 5 - a) Black and white image of the circle 1861b taken at the wavelength 640 nm, b) comparison of a visible reflectance spectrum over the degraded area and an average of 16 pixels over the non-degraded part of the *Orange-4* hue of the circle 1855a and 1861b, c) comparison of the chromaticity diagram b*L* of the degraded (1 pixel) and non-degraded (36 pixels) hues from *yellow* to *orange-yellow-5* of the circle 1861b.

Conclusions

This study highlights that the visual differences between two chromatic circles from the same edition can be greater than those from different editions. In particular, circles grouped together on the basis

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of identical legends share a greater number of material and colorimetric similarities. These observations lead to different hypotheses. Several sets of plates engraved by R-H. Digeon may have been produced for printing in large quantities, and/or some circles may have been reused in later editions, which would explain why the circle is stuck on the page of the book. In any case, the variability observed can depend on both the engraving and the printing stage. Indeed, the engraving step is particularly difficult to reproduce from one batch to another; variations in the density of the resin grains can affect the engraved thickness and, ultimately, the thickness of the applied ink, whereas, the density of the inks, the wiping of the plates, the paper support and the strength of the printing press are all sensitive steps, influenced by the worker's actions during the printing step, which can then lead to variations in the colours of the circle, more or less perceptible to the naked eye. The circle from 1864a is the most different from the others. A change both of printer with the Lamoureux printing house and of engraver with the probable collaboration between the son Antoine René Digeon and the father René Henry Digeon, translated by the legend ‘Digeon sc.’ would justify these changes in terms of ink composition and, consequently, visual appearance. Finally, these results deal with the degradation state of the circles, which permanently alters their visual appearance. Nevertheless, these different circles are nowadays, the witnesses of the challenges overcome by printers and engravers to achieve chromatic circles with a consistent visual appearance between each print, thereby offering the world a unique reference colorimetric system.

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A perceptual assessment of the chromatic scale of uncertainty in hypothetical virtual architectural 3D reconstruction

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Abstract

Chromatic multilevel scales and matrices are popular tools used by scholars to visually communicate uncertainty and other aspects in many scientific contexts, including that of hypothetical virtual 3D reconstruction of lost or never-built architecture. False-colour visualisations play a pivotal role in improving the transparency of the complex inference-based process that is inevitable when dealing with lacking data sets, nevertheless, there are still no standards of reference in this field. This paper investigates this topic and tries to formulate good practices for creating easily readable and effective multi-level chromatic scales that will be applied to shaded 3D models. Furthermore, a newly designed chromatic 7-level scale of colours that empirically proved to perform better than the previous scales will be proposed. The results of this study are supported by an on-field survey administered to 50 users.

Keywords: 3D virtual reconstruction, unbuilt heritage, uncertainty assessment, chromatic scale.

Introduction and background

In the field of hypothetical virtual 3D reconstruction of lost or never-built architectures, quantifying, visualising, and communicating the uncertainty together with documenting the reconstructive process are aspects of well-known importance. The scientific community over the years tried to give an answer to these needs by developing various reconstruction and assessment methodologies, however, in this contest, there are no shared standards of reference yet. The CoVHer Erasmus+ project (CoVHer website, 2022), among other objectives, tries to answer this lack of common ground by developing a series of good practices and a new and standardised methodology for the scientific, hypothetical reconstruction of lost or never-built architecture. The spread use of such a methodology in which the uncertainty assessment is a pivotal part would improve transparency, comparability, and reusability of reconstructive 3D architectural models. Being able to achieve these objectives would comply with the FAIR principles (Wilkinson et al., 2016), the Seville principles (ICOMOS, 2017), and the London charter (Denard, 2012), all of which are foundational reference documents in the field.

The uncertainty assessment object of this study was iteratively developed over the years (Apollonio, 2016; Apollonio et al., 2021, 2024). It is based on a seven-level scale of increasing uncertainty which can be reduced to five and three levels at need (Fig. 1). To each level, a colour, a numerical value, a percentage of uncertainty, and a textual definition are assigned. All these elements were designed to make the scale as user-independent as possible. The uncertainty of the 3D model is assessed element by element and a false-colour view is produced. Publishing these false-colour variants of the model together with the 3D textured or untextured reconstructive versions of the same model would help reduce the risk of generating historical falsehoods and misinterpretations for scholars and laypersons.

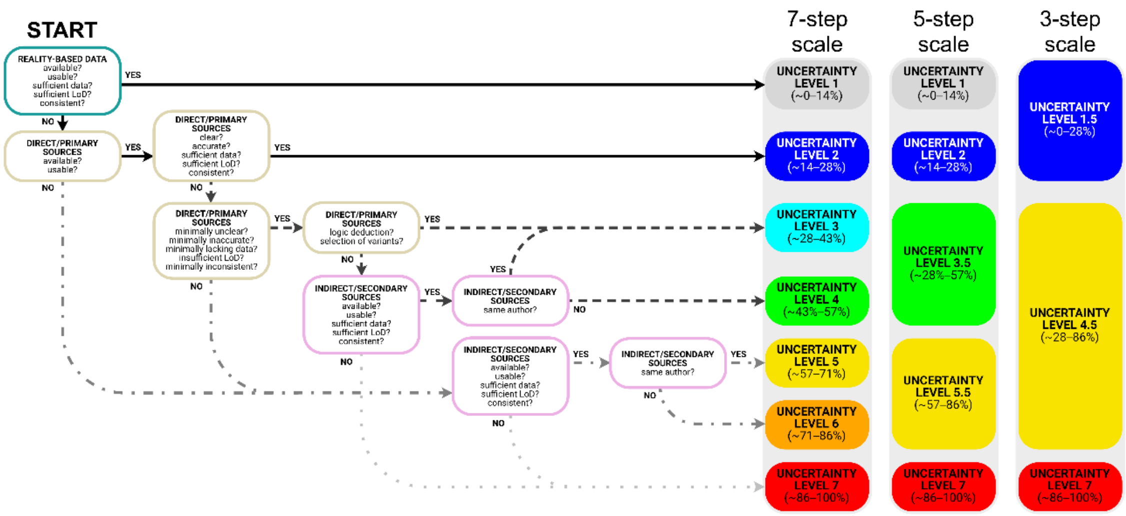

Fig. 1 - Uncertainty yes/no flow chart, elaboration of an image first published in (Apollonio et al., 2024).

It is important to design and use scales that are effective when applied to shaded 3D models while keeping in mind that particular lighting conditions can mislead the correct interpretation of colours (Lafer-Sousa et al. 2015; Rabin et al 2016 ; Adelson, 1995). The reference scale of this study, right from the earliest iterations, used a rainbow colour progression. Even if, in this context, this scale had empirically demonstrated to be capable of achieving consistent recognisability of colours, in some other contexts, similar rainbow-based colour progressions were evaluated as less effective in comparison to other colour schemes (Light and Bartlein, 2004). This raised the question of whether a different colour progression might perform better in our context.

This research, starting from the study of colour scales used in choropleth maps (Brewer et al. 1997) and colour gradients for data visualisation (Reda et al. 2018), and with on-field user's testing, tries to verify experimentally which colour scheme, among the ones tested, is more effective for false-colour visualisation of shaded 3D rendered architectural models, and aims to define good practices and guidelines concerning how the Lightness, Chroma, and Hue parameters (LCH) - as defined for the OKLCH encoding (Sitnik, 2024) - can contribute to achieve more effective results in this context. In the presented experiment various scales are put to the test, 50 users were prompted to look at a series of images of a shaded 3D model coloured with various 7-level colour scales and were requested to match the colours of the various elements of the model to the corresponding colours on a reference sorted legend.

Investigating various colour progressions for user's testing

Numerous colour progressions were studied and considered for the users' testing. Scales from A to F in Table 1, are designed to have uniform perceptive steps while varying only one LCH parameter at a time, all these scales were designed by using the OKLCH Colour picker available online (Sitnik, 2024) limiting the colour gamut to sRGB in order to make them compatible with most displays, and thanks to this tool it was possible to maximise the colour ranges between adjacent steps at given LCH parameter of choice. In particular, on scales A and B, the Lightnesses were set to maximise the Chroma range at the chosen Hues. The same principle was followed for the scales C and D where the Hues were set to maximise the Lightnesses ranges at the chosen Chromas. In scale E, Lightness and Chroma were chosen to maximise Hue intervals, and in scale F the hue range was reduced artificially to make a traffic-light-like scale at constant lightness and chroma. Other traffic-light-like scales which varied all LCH parameters were considered (G, H) because using progressions from red to green might have helped to intuitively interpret the uncertainty levels in this context since laypersons nowadays, in traffic-light-like colour progressions, tend to interpret the red colour as a message for alert/error and green as its opposite, however, these kinds of scales are very poorly perceived by persons with red-green colour vision deficiencies (CVD), so, sadly, they were excluded from the user's testing. Scales from I to L come from well-known colour gradients used in data analysis (Rudis et al., 2024) which in some contexts are considered better alternatives to rainbow gradients because they are more colour-blind friendly. Scales from M to Q are rainbow-like scales, where M and N are well-known (Mikhailov, 2019), O is the rainbow scale with max saturation used in (Apollonio, 2016), P is the variation presented in (Apollonio et al. 2021; 2024), and Q is a new colour scale derived by these first two references, where LCH parameters are varied to make it more colour-blind friendly. From this preliminary investigation, only the most relevant scales were tested in the survey (indicated with * in Table 1). A, C, D, and E scales were expected to perform poorly but they were included in the testing as control scales to investigate how the individual variation of the LCH parameters impacted the perception of colours in a shaded 3D model.

Table 2: investigated 7-level colour scales (* indicates the ones tested in the crowdsourced survey).

	Scales Name	Colour progression in HEX format						
A	Uniform Chroma steps*	#5AF32A	#74EF57	#89EA74	#9BE48B	#ABDEA0	#BAD8B3	#C7D1C5
B	Uniform Chroma steps 2	#F82DF9	#EB52EB	#DE69DC	#CF7ACD	#C585C0	#C088BE	#9E9E9E
C	Uniform B&W*	#060606	#222222	#414141	#636363	#878787	#AEAEAE	#D6D6D6
D	Uniform Lightness steps*	#3D0245	#572060	#733B7C	#905699	#AE72B7	#CD8FD6	#ECADF6
E	Uniform Hue steps*	#EC8DAB	#EB9666	#C0AF4D	#73C385	#2AC4CC	#70B3F7	#BA9CEF
F	Uniform Hue steps 2	#F57FA7	#FB8275	#F28E42	#D9A00E	#B1B228	#7AC05E	#1FC893
G	Traffic light	#7A0403	#FF0000	#FF8200	#FFFF00	#99FF53	#36D000	#00740E
H	Extended Traffic light	#6E0253	#CA0D2E	#FE8506	#FFF019	#63FA0E	#2AAC54	#197F8A
I	Virdis*	#440154	#443983	#31688E	#21918C	#35B779	#90D743	#FDE725
J	Inferno	#000004	#320A5E	#781C6D	#BC3754	#ED6925	#FBB61A	#FCFFA4
K	Magma	#000004	#2C115F	#721F81	#B73779	#F1605D	#FEB078	#FCFDBF
L	Plasma*	#0D0887	#5C01A6	#9C179E	#CC4778	#ED7953	#FDB42F	#F0F921
M	Turbo	#7A0403	#EA4E0D	#F8BE39	#A3FD3C	#19E4B8	#4682F8	#30123B
N	Jet	#7A0403	#FF0000	#FF8200	#FFFF00	#7EFF81	#007FFF	#000080
O	Rainbow (max sat) (2016)*	#FF0000	#FF7F00	#FFFF00	#00FF00	#00FFFF	#0000FF	#FF00FF
P	Rainbowhite (2021)	#FF0000	#FF7F00	#FFFF00	#00FF00	#00FFFF	#0000FF	#FFFFFF
Q	RainbowhiteLCH (2024)*	#800C1B	#CD8503	#FFFF00	#95DB78	#43AAB3	#0C3DFE	#E6E6E6

Designing a new more colour-blind-friendly and effective colour progression

The scale RainbowhiteLCH, shown in Table 1 at letter Q, was derived from the Rainbow scale (O) used in (Apollonio, 2016). In 2021 (Apollonio et al., 2021) the scale was slightly changed to address some issues already evident from preliminary on-field tests (P). In particular, the magenta colour was substituted with white/grey because it was the only level referring to real-world physical evidence (e.g., ruins) while the other levels of the scale referred to inferences from graphical or documental sources so it made sense to differentiate it from the other levels. Furthermore, by removing magenta, the progression from red/orange to green/blue passing through yellow allowed it to get closer to the semaphoric trichromacy and improve the intuitive matching between colours and relative uncertainty. The updated scale also aimed to preserve backwards compatibility with previous works that used the 2016 scale. Lastly, the colours of the new scale were not rigidly imposed with specific RGB values by design, the colours were chosen to be easily nameable (red, orange, yellow, green, cyan, blue, and white), this choice was aimed at fostering the adoption of the scale allowing users to shift them slightly based on various contexts and needs without loosing comparability between different projects. Starting from this scale, the RainbowhiteLCH scale shifts slightly the LCH parameters aiming to improve readability for CVD users, not reducing or even improving the readability for normal colour vision (NCV), while preserving their Hue recognizability for backward compatibility. In particular, the Lightness of the colours at the boundaries of the scale was reduced in order to simplify their discerning for users who struggle to recognise specific hues, this last variation helped

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in particular to differentiate more the red and green which in the new version of the scale are much farther apart in terms of Lightness. A yellow or blue component was added to all the Hues in the red and green proximities relatively, in order to help users with CVD in the red-green spectra to discern those colours better. This LCH manipulation inevitably reduced the perceptual distance (CIEDE2000) between some adjacent colours as shown in Fig. 2 however the progression of colours is now more uniform, and the colours are more differentiated in terms of lightness, without losing the nameability based on their hue. Last but not least the new scale is less punchy and more perceptively harmonious which is considered a nice-to-have feature in some non-academic contexts such as in the field of dissemination (e.g. museums, docufilms) and could contribute to adopting it more often.

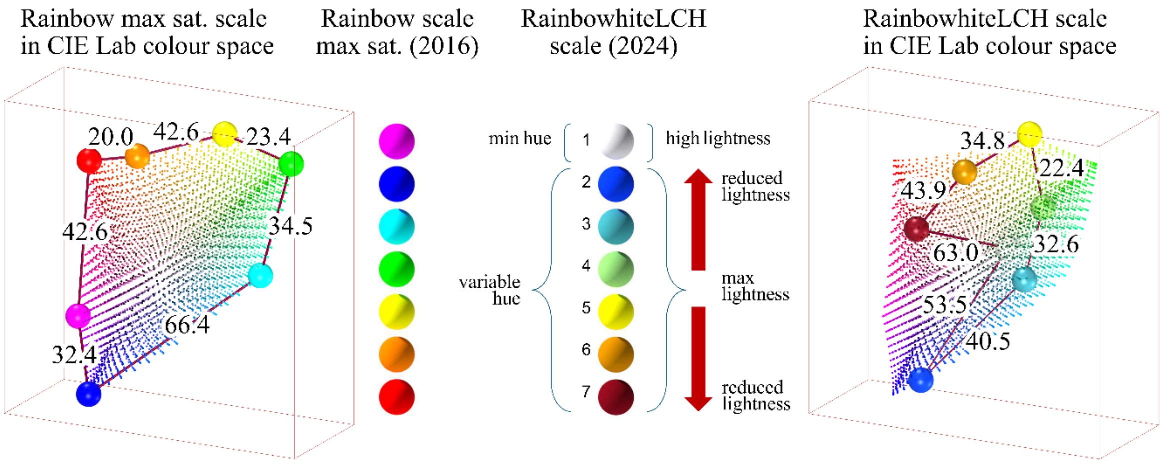

Fig. 2 – (Left) Comparison between the scale used in (Apollonio, 2016) and the new RainbowhiteLCH scale. (Right) RainbowhiteLCH scale visualised in CIE Lab colour space, the numbers between the spheres are the CIEDE2000 (calculated with: http://www.brucelindbloom.com/index.html?ColorDifferenceCalc.html).

To improve the readability of false-colour representation of 3D models it is always better to reduce as much as possible contrast caused by strongly lit scenes, Fig. 3 shows how the readability of the scale improves by using diffuse lights which generate ambient-occlusion-like shadows. However, since this research aims to define good practices to create false-colour scales applicable in various scenarios, the subsequent analyses were all performed on strongly lit 3D models with high contrast between shaded and lit areas to consider the worst, but sometimes used, lighting conditions.

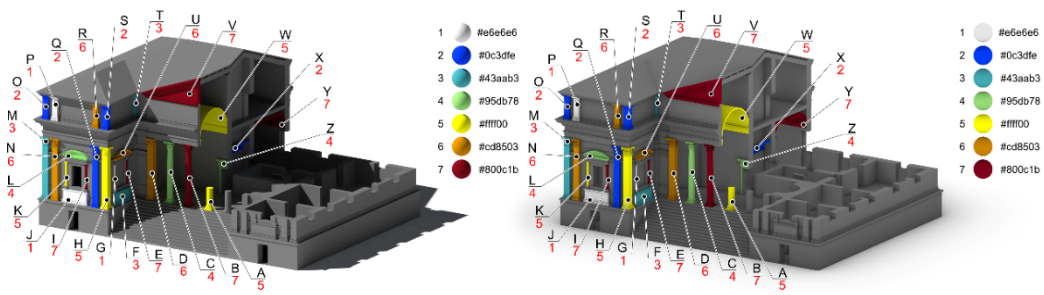

Fig. 3 – Same colour scale (RainbowhiteLCH) with different lighting setup. (Left) Direct light with high contrast, sharp shadows; (Right) diffuse light with uniform soft ambient-occlusion-like shadows.

All the scales presented in Table 1 were applied to a sample 3D shaded model and qualitatively assessed for CVD users by processing them in the Colour-Blindness simulator (Wickline, 2001). A comparison between the Colour-Blindness assessments of scales O and Q is presented in Fig. 4. In O the cyan and green levels and the red, orange and magenta levels are already difficult to discern even for NCV users, while in Q they are easier to recognise thanks to the varied Lightness. In weak CVD simulations, Q manifests clear improvements, while for severe colour-blindness simulations, there is a minor improvement, but some colours are still ambiguous. Monochromacy simulation is completely unreadable for both O and Q.

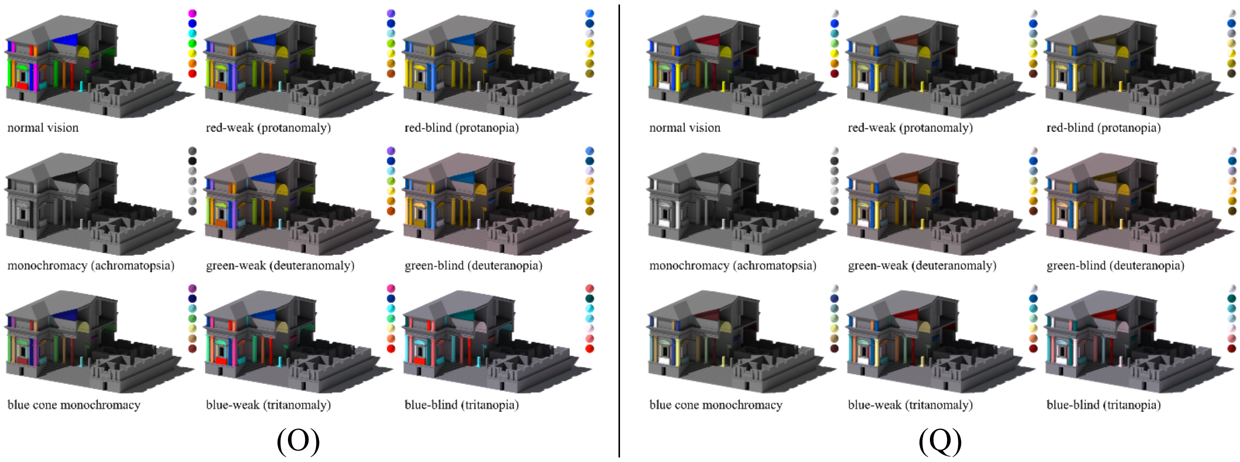

Fig. 4 – Colour-Blindness simulation (Wickline, 2001) of the Rainbow with maximum saturation scale (O) (Apollonio, 2016), and the RainbowhiteLCH scale (Q).

Survey

The survey was designed as follows. In the first two questions, a colour arrangement test (Colblindor, 2021a) and an Ishihara 38 plate test (Colblindor, 2021b) were submitted to all the participants to verify if they had some sort of CVD or if they were using a heavily uncalibrated display, in case of positive result the survey submitted by these candidates were excluded. We chose not to use a designated calibrated display to run the survey because the scales of uncertainty are usually visualised on any type of display, and testing them only on a perfectly calibrated display could have biased the result. Each colour progression selected for the testing (the entries marked with * symbol in Table 1) was applied to various elements on a 3D shaded exemplificative model and a series of rendered false-coloured images were produced (Fig. 5).

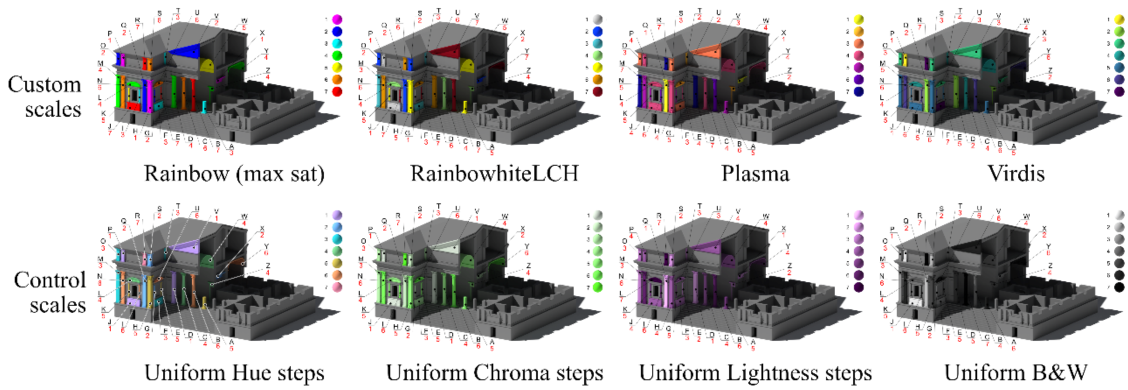

Fig. 5 – The 8 pictures of models submitted to the 50 participants of the survey. The red text indicates the correct answers which were not visible to the participants.

For each image, the participants were requested to match 10 randomly selected elements to the corresponding colour on the reference 7-colour legend, for each question the number of wrong and right answers were registered. After each question, the participants were asked to indicate how hard was the task on a scale from 1 to 10 where 1 was the hardest, and 10 was the easiest.

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Survey results

The results of the survey are reported in Table 2. As expected the control scales with perceptually uniform Chroma and Lightness intervals (A, C, D) performed poorly plausibly because these two parameters are more subject to shifting in a shaded scene depending on lighting conditions. The scale with perceptually uniform Hue steps (E), performed better because, when the light in the scene is white (which was a requirement of this experiment) the colours are less affected by hue shifting due to lighting conditions. However, despite being the scale with the maximum possible hue range in the sRGB gamut, the users still committed several errors, probably due to the fact that in order to have equal lightness and chroma for all steps, the chroma could not be maxed out relative to the selected hue for each step, which caused the colours to be less saturated and thus more susceptible to misinterpretation in a shaded scene. Surprisingly Viridis (I) and Plasma scales (L), despite being more saturated compared to the previous scale (E), in this context performed badly, probably because they cover a small Hue range and rely too much on lightness variation which was proven by the previous tests to be unreliable in shaded scenes. The two better-performing scales were the Rainbow with maximum saturation (O) with 62,50% of candidates who matched correctly 10 colours out of 10, and 27,50% of candidates who matched 9 colours out of 10, for a total of 90% of users who guessed correctly 9 or 10 colours out of 10; and the RainbowhiteLCH (Q) with 87,50% of candidates who matched correctly 10 colours out of 10, and 12.5% candidates who matched correctly 9 colours out of 10, for a total of 100% of users who guessed correctly 9 or 10 colours out of 10.

Table 3: Survey results. The RainbowhiteLCH (Q) outperformed the others, with the Rainbow max sat (O) as a close second.

Correct answers (max 10/10)	Uniform chroma steps (A)	Uniform B&W (C)	Uniform Lightness steps (D)	Uniform hue steps (E)	Virdis (I)	Pasma (L)	Rainbow max sat (O)	Rainbo-white LCH (Q)
10/10	0	0	0	26	7	5	25	35
9/10	0	0	0	9	9	6	11	5
7–8/10	12	1	0	5	18	26	4	0
0–6/10	28	39	40	0	6	3	0	0
10/10 (%)	0,00%	0,00%	0,00%	65,00%	17,50%	12,50%	62,50%	**87,50%**
10/10 + 9/10 (%)	0,00%	0,00%	0,00%	87,50%	40,00%	27,50%	90,00%	**100,00%**

Among the 50 total candidates tested we excluded five who tested positive for CVD, one who clearly answered randomly, and the two worst and two best results for each scale to exclude eventual outliers. Despite the five tested users with CVD do not represent a relevant sample, we can say that the results gathered so far are in line with what was observed in the simulated images produced with the Colour-blindness simulator. Concerning the qualitative opinions of the candidates, they are synthesised in Table 3. The Rainbow scale with max saturation (O) was considered the easiest to use, with the RainbowhiteLCH (Q) placing second. This result is interesting because, in the empirical tests, their ranking was swapped. This is probably due to the fact that colours higher in Chroma stand out more in a shaded 3D scene, however, strongly disuniform perceptual interval might make the closest colours more susceptible to be mistaken for the adjacent ones, in fact, in scale O, the most mistaken pairs of colours were red/magenta, and green/cyan.

Table 4: Candidates' opinions on the ease of the task.

Opinion of the candidates (1=hard 10=easy)	Uniform chroma steps (A)	Uniform B&W (C)	Uniform Lightness steps (D)	Uniform hue steps (E)	Virdis (I)	Pasma (L)	Rainbow max sat (O)	Rainbo-white LCH (Q)
10/10	0	0	0	6	0	1	26	28
9/10	0	0	0	15	1	8	11	5
7–8/10	3	2	4	12	15	17	3	7
0–6/10	37	38	36	7	24	14	0	0
10/10 (%)	0,00%	0,00%	0,00%	15,00%	0,00%	2,50%	65,00%	**70,00%**
10/10 + 9/10 (%)	0,00%	0,00%	0,00%	52,50%	2,50%	22,50%	**92,50%**	82,50%

Conclusions

The novel RainbowhiteLCH scale is a more perceptually uniform variation of the Rainbow scale with max saturation used for the first time in (Apollonio, 2016) and updated in (Apollonio et al. 2021; 2024), it was designed to be more colour-blind friendly by shifting the colours in the proximity of the red and green hues toward the blue/yellow axis, and by varying the lightness and chroma of the most ambiguous colours of the previous scale to simplify their recognisability in shaded scenes (in particular the pairs magenta/red, and cyan/green). The survey was submitted to 50 candidates and empirically revealed that the novel scale improved the recognisability of colours in the exemplificative 3D shaded scene for NCV users. The colour-blind simulation revealed that also users with CVD might benefit from this updated scale. Nevertheless, despite the gathered preliminary data looking promising, a greater sample of users with CVD is required in order to draw robust conclusions for those subjects. The effectiveness of the scale for users with some of the most severe types of CVD is still unsatisfactory, in these cases, a completely different approach should be considered.

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Implementing Generative Artificial Intelligence in Lighting and Color Design: Methodologies, Advantages, and Challenges

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Abstract

In the era of technological innovation, Generative Artificial Intelligence (GAI) is radically transforming spatial conception and experience, particularly in lighting and color design. This integration is revolutionizing the design, management, and experience of interior environments. Through exploration of theoretical principles, practical applications, and technological implications, this synergy is redefining lighting and color design concepts.
This article examines methodologies, benefits, challenges, and future potential of GAI in creating optimal, energy-efficient, and personalized lighting and color solutions. Leveraging techniques like generative adversarial networks (GANs) and deep learning, GAI analyzes extensive data, learns from existing projects, and generates new design configurations.
The process involves collecting detailed environmental data using IoT devices, training generative models on extensive datasets, and generating optimized lighting and chromatic solutions. Advantages include increased efficiency, advanced customization, energy optimization, and expanded creative possibilities. Challenges persist in data quality requirements, technological integration complexity, and implementation costs.
The future of GAI in lighting and color design promises developments in augmented and virtual reality for immersive visualization, integration with renewable energy sources, and unsupervised learning for autonomous solution generation. This integration has the potential to make interior design smarter, more adaptive, and personalized.

Keywords: Lighting design, Color design, Generative Artificial Intelligence, Machine learning, Generative Adversarial Network.

Introduction

Artificial intelligence (AI) has evolved significantly, becoming a popular trend in various fields, including architecture (Wei 2018). Its application in architectural design initially focused on the conceptual phase, where techniques such as text-to-image translation and style transfer were used to generate visual outputs (Mirra e Pugnale 2022). However, the potential of artificial intelligence extends beyond mere visual generation, offering the possibility of developing more autonomous and participatory design systems that enhance the sustainability and overall intelligence of architectural projects. The sub-category of Generative Artificial Intelligence (GAI) is emerging as a driving force that radically transforms the way spaces are conceived and experienced (Frontoni 2023), with increasingly widespread applications in lighting and color. Generative models transform the design process. Additionally, they redefine lighting and color management in interior spaces (Mathew e Mahanta 2020). Traditional lighting and color design relied on empirical rules, manual processes, and designer expertise to manage complex spatial and environmental interaction. With the increase in computational power and the availability of larger datasets, GAI is now capable of analyzing large amounts of data, understanding the dynamics of natural and artificial lighting, material characteristics, and user preferences. Through advanced predictive models, it provides designers with powerful tools. These allow for exploring color combinations, planning optimal lighting distributions, and testing different configurations in simulated environments before implementation. Such capabilities surpass those of traditional design software. These technologies significantly enhance the phases of design,

planning, and implementation, offering more efficient, personalized, and aesthetically innovative solutions (Sokolova e Fernández-Caballero 2015).
This paper aims to analyze the implementation of GAI in lighting and color design, examining current methodologies, benefits, and challenges. By investigating how GAI-driven approaches can achieve efficient, adaptive, and personalized environments, we uncover new opportunities for advancing interior spaces' aesthetic and functional aspects.

Implementation Methodologies

GAI implementation in lighting and color design relies on advanced machine learning and deep learning technologies, divided into three phases: data collection, model training, and solution generation. Generative Adversarial Networks (GANs), introduced by Goodfellow in 2014, are a key technology in this field. GANs consist of two neural networks interacting competitively: a generative network creating new data and a discriminative network evaluating its accuracy. This "adversarial learning" allows for innovative design solutions beyond traditional conventions (Goodfellow *et al.*, 2014).
A crucial part of the AI-based generative design process is the collection of necessary data to train the models. These datasets include:

- Environmental Information: Dimensions and layout of the space.
- Natural Lighting Conditions: Measurement of available natural light (Littlefair, 2011).
- Material Characteristics: Surface reflective and absorptive properties (Boubekri, 2008).
- User Preferences: Functional and aesthetic.

Internet of Things (IoT) devices are used for real-time data collection, allowing precise monitoring of environmental conditions (Putrada *et al.*, 2022).
In the training phase, generative models learn from extensive datasets of existing lighting and color projects, recognizing patterns and correlations between spatial variables, lighting, and color. The goal is to create a model capable of generating innovative and functional solutions based on specific parameters. It has been demonstrated that high-quality datasets significantly improve the generated solution's accuracy and reliability (LeCun, Bengio and Hinton, 2015). The final phase involves generating optimized lighting solutions and color schemes. The AI system considers key parameters such as luminous efficiency, aesthetics, color harmony, contrast, and adaptability to the project context. A promising approach in this phase is the use of Retrieval-Augmented Generation (RAG) models, which enhance the ability to generate relevant and contextualized content (Baduge *et al.*, 2022). The generative model produces a series of proposals, each optimized to meet specific project criteria. This process enhances the designer's role by providing a tool to rapidly explore a wide range of creative possibilities.Implementation requires collaboration between AI experts, lighting designers, and color specialists, leading to innovative, efficient, and highly customized design solutions (Novakovskyi and Yaloveha, 2024).

Practical Applications of GAI in lighting and color design

GAI implementation in lighting and color design has resulted in practical applications transforming the industry. These applications focus on three main areas: lighting optimization, color customization, and energy efficiency.

Designing Optimal Lighting Solutions

A fundamental application of GAI is the ability to optimize lighting in spaces by balancing natural and artificial light. In architecture, light plays a crucial role in defining the atmosphere, functionality, and comfort of an environment.
In the context of lighting design, GANs learn from datasets containing information on lighting patterns, light intensity, color temperatures, and other parameters. These networks gather insights from historical data, developing a comprehensive understanding of lighting styles, user preferences,

and environmental dynamics (Aliakseyeu *et al.*, 2011). Machine learning algorithms process complex models. These adjust lighting by considering variables such as time of day, natural light presence, and activities performed in the space. This training enables GANs to generate innovative and customized lighting solutions (Ren *et al.*, 2023).
Key applications of GAI in lighting design include:

- Advanced Natural Light Simulation: GAI accurately simulates the interaction of natural light with interiors under various conditions, allowing designers to assess its impact on design.
- Energy Efficiency Optimization: Machine learning models calculate the optimal placement of light sources, adjust intensity based on available natural light, and predict energy consumption (Omar, 2023).
- Adaptive and Personalized Lighting: Integration with IoT sensors allows automatic adjustment of lighting based on space occupancy, time of day, and individual user preferences, enhancing both energy efficiency and visual comfort (Basurto *et al.*, 2021).
- Dynamic Lighting Scenario Design: GAI generates complex lighting scenarios that adapt over time, supporting occupants' circadian rhythms and improving well-being and productivity.
- Optimization for Specific Visual Tasks: AI models optimize lighting for specific tasks, enhancing visual ergonomics in work environments (Morina *et al.*, 2023).
- Integration with Architecture: GAI suggests innovative solutions for integrating lighting with architectural elements, maximizing natural light ingress and creating unique and functional lighting effects.

Creating Innovative Color Schemes
Generative algorithms can produce color palettes that adhere to principles of color theory and visual harmony (Mathew e Mahanta 2020). This customization capability surpasses the limits of traditional predetermined color palettes, allowing designers to explore innovative and unconventional combinations (Koh, 2023). This approach helps designers consider color options that might not be immediately intuitive, thereby expanding the creative potential of the design process.
The use of GAI in creating color schemes goes beyond merely selecting aesthetically pleasing colors. These systems generate color solutions that optimize spatial perception by leveraging the complex interaction of color and light. GANs, for example, can produce color schemes that maximize interaction with natural light, creating dynamic visual effects. This approach is particularly relevant in architecture and urban spaces where color perception plays a crucial role in defining spatial experience and visual identity.
One of the most intriguing applications of GAI in the field of color is dynamic adaptation. In interactive environments, AI can modify surface colors in response to environmental or behavioral changes (Ferrara and Bengisu, 2014). This dynamic adaptation can manifest in various ways:

- Response to Lighting Conditions: Adjusting colors to compensate for variations in natural light throughout the day, maintaining a consistent atmosphere or creating gradual transitions that enhance visual comfort (Mathew e Mahanta 2020).
- Adaptation to User Activity: Modifying color schemes to support different activities in multifunctional spaces, such as shifting from stimulating tones for work to more relaxing colors for rest (Rangel and Matos, 2021).
- Preference-Based Customization: Adapting color schemes to specific occupant tastes (Lee, 2004).
- Response to Environmental Factors: Changing colors in response to factors like temperature, humidity, or air quality in urban contexts, creating a visual connection between the built environment and environmental conditions (Acampora and Loia, 2009).

These applications demonstrate how GAI is transforming the fields of lighting design and color design by offering more efficient, personalized, and adaptive solutions that significantly enhance environmental quality.

Advantages of Implementing GAI in Color Design and Lighting Design

The integration of Generative Artificial Intelligence (GAI) in color and lighting design has significantly transformed creative and technical processes. GAI enhances efficiency, personalization, and innovation while contributing to energy-sustainable solutions. A primary benefit is the remarkable speed at which design solutions can be generated. Generative neural networks process thousands of variables rapidly, developing color schemes and lighting configurations more efficiently than traditional methods. This acceleration allows designers to explore a wider range of options and identify optimal solutions quickly (Oh *et al.*, 2019).

GAI excels in creating personalized solutions by adapting lighting and color to user preferences. Through data analysis from sensors and user interactions, generative models produce configurations reflecting personal tastes and specific needs (Edwards, 2016). This capability extends to designing more inclusive environments, considering diverse user categories, including individuals with visual or sensory impairments (Aranda-Muñoz *et al.*, 2022).

The technology significantly expands creative possibilities by generating solutions that might not emerge through traditional methods (Frontoni, 2024). Generative models combine design elements in innovative ways, exploring complex configurations that are challenging to conceive manually (Saadi and Yang, 2023). GAI acts as a creative collaborator, providing inspiration and alternatives that enrich the ideation process. Furthermore, GAI revolutionizes design through advanced simulations and predictive analyses, optimizing the creative process. Designers can predict the performance of their creations before implementation, allowing timely corrections. The intuitive visualizations generated by AI facilitate understanding of design choices, improving communication and decision-making.GAI also promotes multidisciplinary collaboration, facilitating interaction among architecture, engineering, computer science, and behavioral sciences. This collaborative potential enhances individual projects and contributes to the industry's overall progress, promoting sustainable, inclusive, and future-oriented practices.In conclusion, GAI's advantages in color and lighting design are evident in efficiency, personalization, sustainability, and creative innovation.

Challenges and Limitations of GAI in Color Design and Lighting Design

Despite its many advantages, integrating GAI into color and lighting design has several challenges. A primary concern is the quality and accessibility of data required for effective AI model training. Incomplete or biased datasets can lead to inaccurate or suboptimal results, potentially compromising the universal applicability of generated solutions.

The technical complexity of integrating AI with IoT sensors for real-time data collection requires advanced infrastructure and specialized expertise, making GAI adoption challenging, especially for smaller enterprises. High implementation costs, including computational resources and staff training, pose substantial barriers for many design studios and professionals.

Practical application of GAI tools in product design faces challenges in both "getting the right design" and "getting the design right" (Hong *et al.*, 2023). Generating lighting solutions that dynamically adapt to various environmental or behavioral conditions in real-time requires GAI to consider multiple variables simultaneously, a computationally demanding task. Accurate reproduction of color across different devices and lighting conditions remains a persistent challenge for GAI systems, which may not always capture or faithfully reproduce crucial color nuances (Liu *et al.*, 2023).

From an ethical standpoint, the use of AI raises issues related to privacy and data protection (Loré, 2019). GAI in lighting design often relies on collecting detailed data about user habits and preferences through sensors and IoT devices. Although they are distinct documents with different purposes and scopes, both the UNESCO Recommendation on the Ethics of AI adopted in 2021 (UNESCO, 2021) and REGULATION (EU) 2024/1689 of 2024 (*Regulation - EU - 2024/1689 - EN - EUR-Lex*, 2024) emphasize the importance of ensuring individual privacy and personal data security.

AI can introduce biases into decision-making processes when models produce results influenced by skewed or non-representative data (Ferrara, 2023). Industry resistance to change also poses a challenge, as many professionals may view AI adoption as a threat rather than an opportunity, necessitating training and support strategies to facilitate innovation adoption.

Future Potential and Developments

Recent research highlights the transformative potential of GAI in design and creativity, with key developments anticipated in the integration of augmented reality (AR) and virtual reality (VR), advanced unsupervised learning techniques, and integration with renewable energy sources. The combination of GAI with AR and VR technologies promises to enhance spatial understanding and decision-making in color and lighting design (Parati and Zolotova, 2024), enabling real-time collaborative environments and promoting innovation through direct interaction among professionals from different disciplines (Yuan, 2024).

The future of GAI will see increased use of unsupervised learning techniques, allowing AI systems to identify patterns and relationships without large predefined or manually annotated datasets (Sanhita Kar *et al.*, 2023). his approach reduces dependency on human data and increases AI models' ability to generate creative and unpredictable solutions capable of adapting to new or complex situations (Franceschelli and Musolesi, 2023). In the realm of lighting design and color design, similar techniques could be applied, enabling AI to explore color combinations and lighting solutions never considered before, surpassing traditional aesthetic conventions. This innovative approach could lead to lighting and color configurations that dynamically respond to environmental and social factors, opening new frontiers in design (Parati and Zolotova, 2024). A recent study using GAI tools (Vizcom e Midjourney) to create futuristic residential lighting environments demonstrated AI's ability to generate not only design objects but also atmospheres and spatial configurations capable of influencing communication and social relationships (Longo, A Middleton and Albano, 2024). The evolution of AI in lighting design could also consider non-visual effects of light, such as impacts on circadian rhythm and mood. While AI can generate innovative solutions, integration with human expertise remains crucial. The quality of AI-generated solutions relies on the "Effectiveness Trilogy": Expertise, Experience, and Usability (Freese, 2023). Designers will need to learn how to effectively use prompts and images to control AI outputs, balancing creativity with functionality. The interpretability of AI decisions remains a significant challenge, requiring new approaches for validating and interpreting results.

Conclusions

Generative Artificial Intelligence (GAI) is emerging as a transformative force in lighting and color design. This study has explored implementation methodologies, practical applications, advantages, challenges, and future potentials of GAI in this context. Advanced techniques like machine learning, deep learning, and particularly Generative Adversarial Networks (GANs), demonstrate a remarkable ability to generate innovative design solutions optimizing luminous efficiency, aesthetics, and personalization. Integration with emerging technologies like the Internet of Things (IoT), augmented reality (AR), and virtual reality (VR) further amplifies application possibilities. The benefits of implementing GAI are significant, including increased efficiency and speed in the design process, advanced solution personalization, energy optimizations, and exploration of creative solutions. However, challenges such as the need for high-quality data, technological integration complexity, high costs, and ethical considerations must be addressed. GAI redefines the boundaries of creativity and efficiency, offering solutions beyond human capabilities and enabling responsive, sustainable, user-centered environments. Looking to the future, GAI has the potential to revolutionize how we conceive and interact with illuminated and colored spaces. A balanced approach integrating human expertise with AI capabilities is crucial, as is interdisciplinary collaboration among designers, engineers, scientists, and AI professionals. Ultimately, GAI in lighting and color design is a catalyst for broader change in how we design and experience spaces. Implemented thoughtfully and responsibly, GAI can significantly enhance our quality of life by creating more comfortable, efficient, and stimulating environments. The future of lighting and color design is bright, colorful, and intelligent, thanks to the synergistic integration of human creativity and artificial intelligence.

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PBR material: a comparison between rendering for accurate material color reproduction. A case study

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Abstract

Physically-Based Rendering (PBR) is gaining popularity in rendering applications due to its ability to generate realistic visuals by mimicking light's and materials physical properties. This strategy improves the quality and uniformity of visuals on different systems, making it a preferred choice for artists, designers, and developers. However, transitioning from non-photorealistic rendering methods to PBR presents challenges, such as adjustments to lighting configurations and material setup. Understanding the differences in light interaction with surfaces is crucial for a smooth transition, necessitating education and training for those involved. PBR consists of two main workflows: metallic and specular. The study compares the strengths and limitations of each workflow, considering criteria such as user-friendliness, adaptability, and accuracy in mimicking real-life substances.

Keywords: Physically-Based Rendering (PBR), real-time rendering, color accuracy, realistic imaging, shading models, material properties.

Introduction

The Physically Based Rendering (PBR) model is a rendering technique designed to accurately simulate light interaction with surfaces based on their physical and optical properties. It relies on core principles such as specular and diffuse reflection (through a correct definition of the BRDF), energy conservation, and the Fresnel effect. PBR materials are characterized by parameters like roughness and glossiness, which define their surface characteristics and influence how light is scattered. The model employs two primary workflows: the metallic workflow, which categorizes materials as metals or non-metals, and the specular workflow, which provides greater control over reflectivity and color for various materials. This article will explore these workflows through a case study using Unity software, demonstrating their practical applications and highlighting the importance of maintaining color accuracy in material rendering.

Theoretical Model

Physically Based Rendering (PBR) is a rendering approach that aims to simulate the interaction of light with surfaces in a way that is consistent with the physical properties of materials. PBR materials are grounded in several core principles that govern their behavior: *Diffuse and Specular Reflection (BRDF)*, *Energy conservation and Microfacet theory, Fresnel Effect, Roughness and Glossiness* (Pharr, Jakob and Humphreys, 2023).

1. Specular and Diffuse Reflection

Specular reflection is the process of light radiation being reflected at a surface, where the incident light ray undergoes reflection and propagates in an opposite direction. The Angle of Reflection on a flat surface is equal to the Angle of Incidence, but irregular surfaces can cause random variations in the reflected direction. Surfaces with more roughness will exhibit larger and less luminous highlights,

while smoother surfaces preserve the focus of specular reflections, enhancing their brightness and intensity.
Diffuse reflection is the scattering of light in many directions upon hitting a surface, resulting in a soft, non-mirror-like appearance. In dielectris the light ray passes from one medium (air) to another (the dielectric) and is scattered multiple times inside the object. Then, it is refracted again out of the object, making its way back to the original medium in a lot of a diffeent directions. Metals strongly absorb light once it enters the surface, preventing subsurface scattering, thus, the concept of diffuse reflection doesn't really apply to metals in the same way. If diffuse reflection occurs on metals, this is due exclusively to the surface micro-roughness of the material.
Metals with diffuse properties exhibit a high degree of absorption, ensuring that refracted light is likely to be fully absorbed. This means that the spatial separation between entry and exit locations can be disregarded (Bennett, 2022). The Lambertian model, commonly used for diffuse reflection, does not explicitly consider surface roughness, but models like Oren-Nayar do. The Lambertian model is widely used for diffuse reflection for its simplicity, but it fails to capture the effects of surface roughness. More advanced models, such as Oren-Nayar, have been developed to address this limitation by explicitly considering surface roughness in their formulations (Oren and Nayar, 1995)

2. *Energy conservation and Microfacet theory*
The total energy of light reflected is less than or equal to the energy of incident light (Pharr, Jakob and Humphreys, 2023). Energy Conservation plays a vital role in physically-based rendering solutions. It states that the total amount of light re-emitted by a surface (reflected and scattered back) is less than the total amount it received. The light reflected off the surface will never be more intense than it was before it hit the surface. Energy conservation is not automatically calculated by the shader in physically based rendering (PBR). The Bidirectional Reflectance Distribution Function (BRDF) models play a crucial role in ensuring energy conservation, together with microfacet theory. BRDFs are designed to conserve energy by ensuring that the total reflected light does not exceed the incident light energy. This is achieved through the normalization of the BRDF and the use of microfacet theory to simulate realistic surface reflections. Microfacet theory uses a Microfacet Distribution Function (MDF) to describe the orientation of the microfacets on a surface (Cook and Torrance, 1982). Common distributions include the Beckmann and GGX distributions (Walter *et al.*, 2007). The MDF helps determine how many microfacets are oriented towards the incoming light direction. It yields a finite value contributing to the overall reflectance without exceeding the incident light.

3. *Fresnel*
The Fresnel Effect, as observed by French physicist Augustin-Jean Fresnel, states that the amount of light you see reflected from a surface depends on the viewing angle at which you see it. The Fresnel effect is greater in dielectrics than in metals. The Fresnel formula describes how light is reflected and refracted based on the angle of incidence (Hecht, 2017). PBR models automatically calculate Fresnel effects based on the material's index of refraction and roughness, ensuring realistic results without requiring manual adjustment from the user. These calculations are performed in real-time by the rendering engine (Pharr, Jakob and Humphreys, 2023).

4. *Roughness and Glossiness*
PBR materials utilize parameters such as roughness and glossiness to define the surface characteristics. Roughness quantifies the microfacet distribution, affecting how light is scattered. A low roughness value results in sharp reflections, while a high roughness value leads to diffuse scattering. These parameters are crucial for simulating a wide range of materials, from smooth metals to rough surfaces like concrete. Glossines is the inverse of the Roughness.

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PBR materials are typically defined by a set of key properties, colors, or textures that dictate their appearance. *Albedo* (or *Base Color*) is a property that represents the inherent color of the material, independent of lighting conditions, and describes the portion of incoming light that a surface reflects diffusely. It is often stored as a texture map. *Metallic* is a parameter that indicates whether a material behaves like a metal. Metallic surfaces reflect light differently than non-metallic surfaces, with metals exhibiting high reflectance and little to no diffuse reflection. *Roughness/Smoothness* controls the microfacet distribution and influences the sharpness of reflections. It is represented as a grayscale texture. A smoothness map is the inverse of a roughness map. *Normal Map* is a texture that provides additional detail to the surface by altering the surface normals, allowing for the simulation of fine surface features without increasing geometric complexity. *Ambient Occlusion* simulates the soft shadows that occur in crevices, corners and areas where light is occluded. It can be used in computer graphics to simulate the way light is naturally blocked or occluded in certain areas of a 3D scene to enhance the depth and realism of a material. In this paper, we will not consider this property since it is primarily an empirical technique rather than a strictly physically-based phenomenon. It does not account for direct light sources, reflections, or complex light interactions such as color bleeding. It simplifies the lighting model to enhance depth and realism without fully simulating the physical behavior of light. Thus, it does not align with physical accuracy (Möller, Haines and Hoffman, 2018).

5. Metallic and Specular Workflow

The construction of a PBR material can be approached using two primary methods: the metallic workflow and the specular workflow. Metallic workflow categorizes materials into two distinct groups: metals and non-metals (dielectrics). The specular workflow enables accurate control of reflectivity and color values for any material, regardless of its nature.

The **metallic workflow** simplifies the material definition by focusing on the physical properties of metals versus non-metals and in most CAD applications the user can input specific properties:

- **Metallic Property**: This is a binary value (0 or 1) that indicates whether a surface is metallic. Metals reflect light differently than non-metals; they tend to have a strong specular reflection and little to no diffuse reflection. If it is possible to input a greyscale map, that tells the shader whether the colored portion is made of metal or not. Metal is represented by white, while non-metal is represented by black.
- **Base Color**: In this workflow, the base color of a metallic surface is often derived from the color of the metal itself, which affects how it reflects light. Non-metallic surfaces, on the other hand, will have a more pronounced diffuse reflection. It is often represented by a base color or texture.
- **Roughness map**: Roughness maps are grayscale textures that indicate the micro-surface details of a material. Each pixel in a roughness map corresponds to a specific area on the surface, where the intensity of the pixel from black to white determines the roughness level. *White* (or light gray) indicates a rough surface that scatters light in many directions, resulting in a diffuse reflection. *Black* (or *dark gray*): represents a smooth surface that reflects light more directly, leading to sharper specular highlights.

The metallic workflow is particularly effective for rendering realistic metal surfaces, as it captures the unique way metals interact with light, emphasizing their reflective qualities while minimizing diffuse contributions (Möller, Haines and Hoffman, 2018).

In contrast, the **specular workflow** focuses on defining materials based on their reflective properties. In this model, surfaces are characterized by their diffuse and specular components:

- **Diffuse Reflection**: This represents the light that is scattered in many directions when it strikes a rough surface. It is often represented by a base color or texture.
- **Specular Reflection**: This refers to the shiny highlights seen on surfaces, which occur when light reflects off a smooth surface. The specular component is controlled by parameters such as the intensity and color of the specular highlight.

- **Glossiness map**: grayscale textures that indicate the glossiness or smoothness of a material's surface. Each pixel in a glossiness map corresponds to a specific area on the surface, where the intensity of the pixel from black to white determines the glossiness level. *White (or light gray)*: indicates a highly glossy surface that reflects light sharply, resulting in pronounced specular highlights. *Black (or dark gray)*: represents a matte surface that scatters light more diffusely, leading to softer and less defined highlights.

This allows for a wide range of materials, from matte to glossy surfaces, to be accurately represented (McDermott, 2018).

Methods

A case study utilizing Unity software will illustrate the practical application of these workflows. It will demonstrate how to implement PBR techniques in the application, highlighting the necessary adjustments to material setup and emphasizing user-friendliness and adaptability in real application design problems. The metallic and specular workflows in Physically Based Rendering (PBR) have distinct effects on the color appearance of materials. Thus, a series of sample object with different materials will be studied to evaluate if they exhibit distinct characteristics in both workflows, allowing for a clear demonstration of the differences in how materials are rendered.

To achieve physically accurate rendering using PBR (Physically Based Rendering) materials, both with the metallic and specular workflows, it is essential to use textures with an sRGB profile (IEC, 1999). These textures should be generated using calibrated tools and under controlled lighting conditions. In fact, all rendering software requires images in sRGB format as input, as this profile ensures a correct representation of colors and brightness, which is vital for visual accuracy in the final images. The use of calibrated tools helps minimize discrepancies between measured values and displayed ones, contributing to more accurate analysis of rendered scenes. Additionally, controlled lighting is crucial for maintaining consistency between textures and rendering conditions, ensuring that materials react realistically to light (Guarini and Rossi, 2021).

Metallic Workflow

In the metallic workflow, the base color of a metallic surface is derived from the inherent color of the metal itself. This color affects how the material reflects light. For example:

- Copper: has a reddish-brown base color that results in warm, reddish reflections.
- Gold: has a yellow base color that produces golden reflections.
- Silver: has a gray base color that leads to cool, silvery reflections.

The metallic property also influences the color of specular highlights. Metallic surfaces tend to have sharper, more defined highlights that closely match the base color.

Specular Workflow

In contrast, the specular workflow separates diffuse and specular reflections, allowing for more control over the material's color appearance.

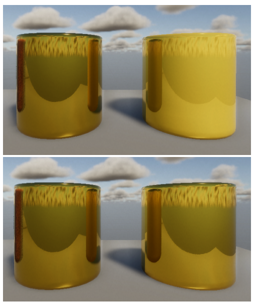
- Diffuse Color: represents the base color of the material, similar to the metallic workflow. It determines the overall hue of the surface.
- Specular Color: controls the color of the specular highlights. It can be adjusted independently from the diffuse color, allowing for more flexibility in achieving desired color effects.

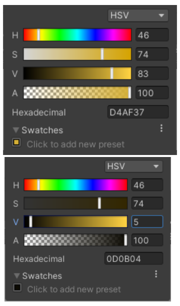
Specular highlights in the specular workflow are typically lighter than the base color, often white or a lighter shade of the diffuse color. The intensity and sharpness of the highlights are controlled by the shininess or glossiness parameters.

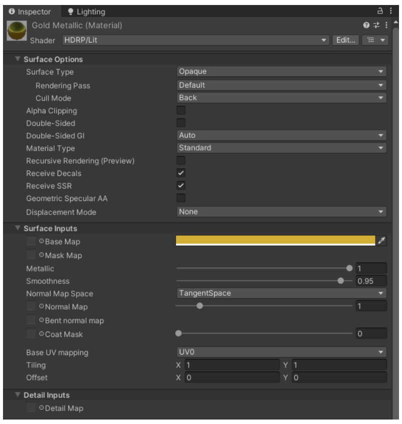
In a Unity scene, some vases have been placed on a table. To ensure maximum fidelity and photorealistic quality, the "High Definition Rendering Pipeline" (Unity Technologies, 2024) was used. The materials created to be assigned to these vases have been setup with Unity's Lit shader (*Lit Shader | Universal RP | 12.0.0*, 2023). All tests were conducted under the same lighting conditions, given by a sun obtained through a directional light, and by an HDRI map to simulate the light from the sky and its reflections on the objects used.

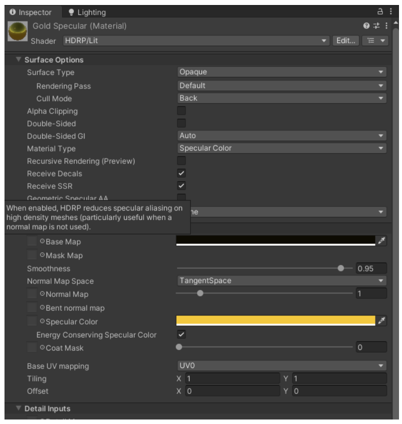
GOLD - The first test was made with a metal gold-type material, with homogeneous color and without texture. Both were given the same HSV color color value on Base color, 46%, 74%, 83%. In the first material created, which in the Lit shader is set to the metallic workflow by default, the « Metallic » parameter has been set to 1. In the second material, the "Material type" has been changed to "Specular color", thus enabling the specular workflow (Unity Technologies, 2024). Since, in this case, the color of reflections and highlights are not automatically affected by the base color, the HSV values have been copied from the base color in the « Specular color » slot. The "Energy conserving specular color" option has been set to ensure that energy conservation is respected. The « Smoothness » value has been setup at 0.95 in both workflows. In the Unity application, the roughness map is never used, and it is replaced by the smoothness map, its inverse, in both workflows. Compared to the original base HSV color, the Metal workflow material applied to a sample vase appears more faithful and was obtained more easily, having set only the metallic parameter to 1. The sample where the specular workflow was applied returns a strongly lighter result. Note that even if the « Energy conservation specular color » is on, the base color Value has to be manually decreased to 5% in order to respect energy conservation and obtain a coherent result as the one obtained with the Metallic workflow.

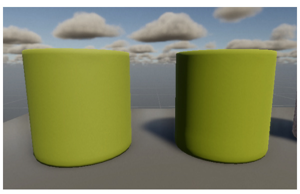
RUBBER - Another test was done with a material of homogeneous color and low specular reflection, such as rubber. The base color has been set to HSV values 68% 72% 50%. Initially, a material with a metallic flow was created, setting a "Smoothness" of 25%. In the corresponding specular workflow, the base color and smoothness have been left unchanged, while the "Specular color" slot has been set to 10%. The item "Energy conserving specular color" has no effect in this case because the Energy conservation is already satisfied with the parameters used. The two samples on which the studied materials were applied did not present substantial differences in terms of color and brightness, but the second required more input from the user.











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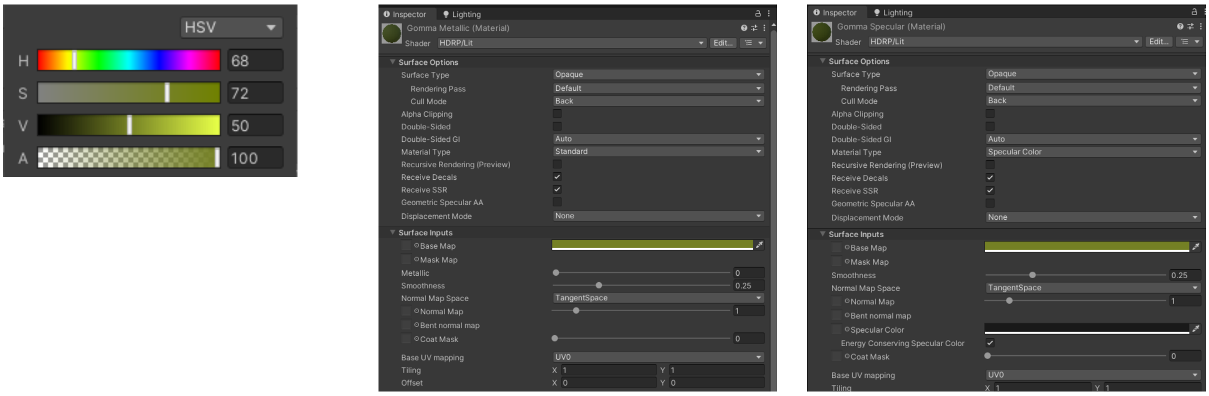

Fig. 1 – GOLD and RUBBER: Left sample, metallic workflow. Right sample, specular workflow. In the specular workflow golden sample, the base color was decreased, even if Energy conserving was enabled.

COPPER - Another material considered is a metal without a homogeneous color, with a diffuse color characterized by a texture, such as copper. In both workflows, the same sRGB color profile map was inserted as a « Base map ». In the first material, which is set to the metallic workflow by default, the « Metallic » parameter has been set to 1. In the second material, the "Material type" has been changed to "Specular color", thus enabling the specular workflow (*Unity - Manual: Metallic vs. specular workflow*, 2024) Since, in this case, the color of reflections and highlights are not automatically affected by the base color, the map has been copied from the base color in the specular slot. The "Energy conserving specular color" option has been set to ensure that energy conservation is respected. The « Specular color » slot was also set to RGB values 250,208,192 as suggested for the copper reflection value in the PBR guide (McDermott, 2018). The « Smoothness » value has been left unchanged in both workflows. Compared to the original texture of the base color, the sample vase where it was applied appears more faithful and was obtained more easily, having set only the metallic parameter to 1. The sample object where the specular workflow was applied returns a less contrasty albedo texture and more saturated color reflections and also requires more inputs from the user. The differences between the two color renderings decrease when the same smoothness map is inserted (in Unity in the « Mask map » slot as the Alpha channel of an image *.tiff).

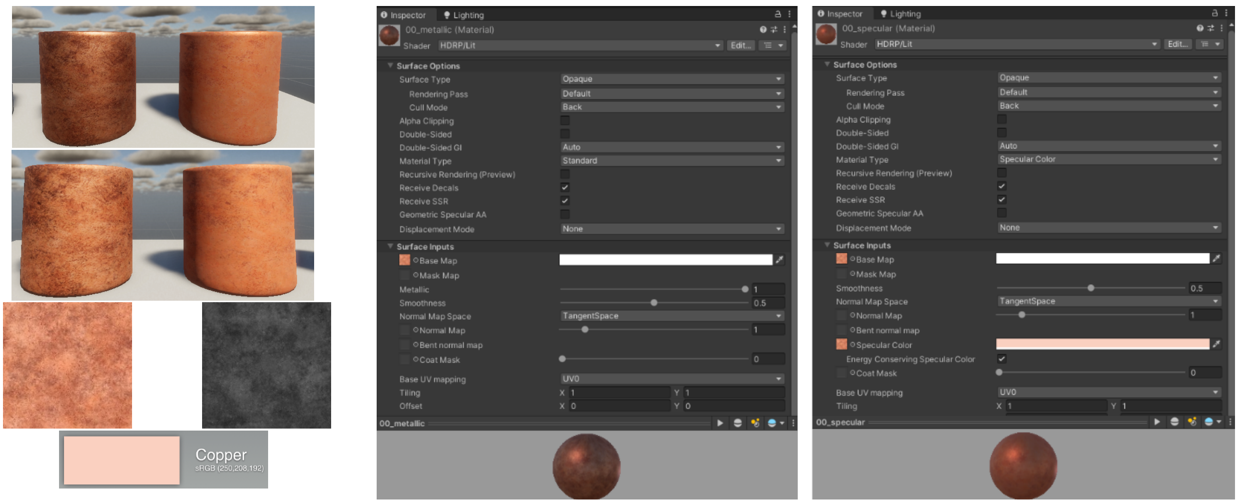

Fig. 2 – COPPER: Left sample, metallic workflow. Right sample, specular workflow. In the latest, a less contrasty albedo texture and more saturated color reflections are evident. The chromatic difference between the two workflow decreases when it is inserted a smoothness map, instead of leaving a numeric value.

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LEATHER - The same procedure was followed to simulate a slightly shiny and bumpy dielectric material, such as leather. Following the metallic workflow, the "Metallic" property has been set to 0. The "Mask map" was used to insert the smoothness map, which automatically determined how much specular light is reflected. Finally, a "Normal map" has been inserted to simulate the surface leather texture. Following the specular workflow, the Material type has been set to "Specular color". The same smoothness map has been inserted through the "Mask map". The "Specular color" slot has been manually set to the highest value within the range of 2-5%. The range on which to act is very narrow because the value between most common dielectric materials doesn't change drastically (Hecht, 2017). The "Energy conserving specular color" option has been set to ensure that energy conservation is respected. The two samples thus assigned are very similar in tonality, but the material created with the specular workflow is slightly darker. However, the user has the possibility to increase the brightness by acting on the sRGB values of the "Specular slot," thus exceeding the physical value above suggested for dielectric materials.

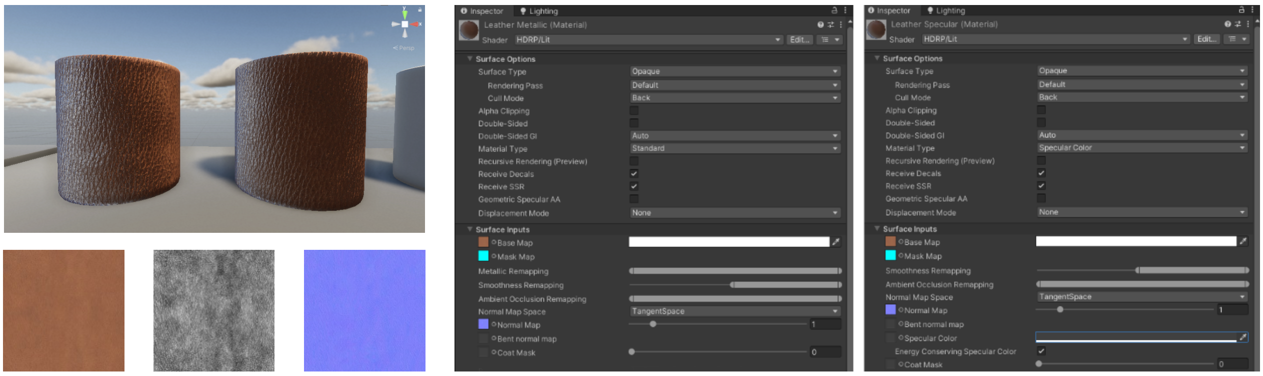

Fig. 3 – LEATHER: Left sample, metallic workflow. Right sample, specular workflow. The specular workflow renders a slightly darker material. To compensate for this difference, incorrect physical specular values for dielectric materials should be used.

Results

The analysis demonstrates that both the metallic process and specular workflow in PBR significantly affect color fidelity. The metallic process is particularly effective for materials that can be distinctly classified as metals or non-metals, ensuring accurate color representation based on their reflective properties and maintaining user-friendly input. In contrast, the specular workflow provides greater flexibility in manipulating reflectivity and color across a wider range of materials, allowing for enhanced color fidelity in diverse applications although increasing the possibility of incorrect user input. The case study in Unity has showcased the implementation of these workflows, emphasizing the importance of maintaining color accuracy in real application design problems.

When comparing the two workflows:

- **Metallic surfaces** tend to have a more uniform color appearance, with specular highlights closely matching the base color.
- **Non-metallic surfaces** in the specular workflow allow for more independent control over diffuse and specular colors, enabling a wider range of color effects.

Copper, for example, would have a reddish-brown base color in both workflows, but the metallic workflow would automatically produce sharper, warmer specular highlights, while the specular workflow allows for more flexibility in adjusting the highlight color. The metallic workflow emphasizes the inherent color of metals and their unique specular reflection properties, while the specular workflow provides more control over diffuse and specular colors for a broader range of materials, requiring more tuning by the designer.

Discussion/Conclusions

The transition from non-photorealistic rendering to physically-based rendering (PBR) introduces significant opportunities and challenges for rendering applications. PBR enhances visual realism by accurately simulating the physical properties of light, yet it necessitates a comprehensive understanding of light interactions with surfaces, which sometimes complicates material setup. Designers must choose between the metallic process and specular workflow, influenced by the materials being rendered and the desired realism. This choice affects flexibility and fidelity in visual outputs. Professionals in visualization and interactive media encounter a steep learning curve when shifting from traditional rendering methods to PBR, requiring skills that extend beyond basic texture mapping. To facilitate this transition, targeted education and training in PBR principles are essential. As PBR techniques evolve, continuous research and development will be crucial in addressing emerging challenges and improving rendering quality and efficiency..

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Color and Restoration

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Silent Film Colourisation Process: From Recipes to Film Laboratories

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Abstract

During the silent era, films were coloured using various experimental processes. Some techniques were tested on a single film, while others were successfully adopted by laboratories in different countries. The three most common film colouration process were pochoir, tinting and toning. Even if these processes were standardized and described in manuals there were always a margin for modifying the recipes and create different shades of colours.

A large part of silent films preserved in archives present these three colour techniques. Knowing in detail the nature of colours is important for planning preservation strategies and for recreating colourations in digital restoration processes. We compare colour recipes contained in lab manuals with the results of non-invasive and micro-invasive methods of analysis (surface-enhanced Raman, Fourier-transform infrared and visible spectroscopies) to understand which are the real components and how closely they correspond to the original formula.

We focus our research on five frames from French and Italian films: a combination of yellow-orange tinting and pochoir from a film Pathé (1907 - 1909); a red tinting intertitle from Tiziano Film production company (1920 - 1921); a yellow tinting frame from an unknown French film (post 1909); a red tinting frame from *La bocca suggellata* (Michele Malerba, 1920); a combination of blue tinting and green toning from an Italian film (end of 1910s beginning of 1920s).

These frames come from film materials developed in Italian or French laboratories, so we selected two manuals published in these countries: Vittorio Mariani, *Guida pratica alla cinematografia* and *Le film vierge Pathé. Manuel de développement et de tirage*. Both contain recipes for colouring films fixing previous common practices.

The analytical methods were chosen because of their specificity towards molecular structures and their suitability for the identification of organic dyes and/or inorganic colouring compounds.

Keywords: tinting; toning; pochoir; silent film, SERS spectroscopy; visible spectroscopy; FTIR spectroscopy

Introduction

The different activities connected to film conservation, preservation, and restoration have developed in relative isolation and have only recently been connected to the broader field of cultural heritage conservation practices. The main reason of this isolation and the lack of scientific studies is due to the short history of the medium (Cherchi Usai, 2010). For this reason, non-invasive and micro-invasive analysis, common practices in the cultural heritage field, have been very rare in film conservation and only adopted recently.

In this contribution we focus on the application of non-invasive and micro-invasive analysis to the colour in silent film. From the long-term conservation point of view, understanding the nature of the components of a colour and how they decay is important for creating a better long-term preservation plan. From the perspective of the film restoration (photochemical, digital or hybrid), it is important for a more precise characterization and reconstruction of colourisations. For example, the frame below (fig. 1) is an unknown Ambrosio film, with a faded yellow tinting and traces of another colour on the side. In this case, it's an isolated fragment and we don't have a colour reference in other scenes, we don't know the shade of the original yellow (light yellow, orange / yellow, acid green / yellow etc) and if the red in the side is a trace of the colour of another scene or another kind of pigment.

Fig. 1 - Film Ambrosio (1907 - 1909)

In others case the colour is not visible anymore or we have only few traces.

The aim of this contribution is to compare colour recipes contained in laboratory manuals with the results of non-invasive and micro-invasive methods to understand which the real components are, because many variations could be made to the original formula. All the information collected will serve as a guide for characterizing colour, understanding colour deterioration, and establishing better conservation and restoration strategies.

Colourization Techniques

In the silent era films were coloured utilizing a variety of processes, many experimental, some never actually applied, and others used for just few films. For an in-depth study of all these techniques with samples and literature, the main reference is the online database Timeline of Historical Film Colour created in 2012 by Barbara Flueckiger and her collaborators (Flueckiger, 2012 ff.).

Despite this great variety of experimentation, the most common film colourisation processes were three: pochoir, tinting and toning. These techniques were simple to achieve and could be standardised to fit in the workflow of film laboratories. The first technique is pochoir or stencil colour obtained by colouring defined areas of the images frame by frame. This technique has been used from 1903 and descend from the photographic retouch and magic lantern slide painting. At the beginning, the colour was applied manually by hundred of women using stencil then, to make the process faster, by machines. Despite this improvement the pochoir process remain too slow: Vittorio Mariani write in his manual (Mariani, 1916) that this technique is long and expensive, and not necessary for a modern film laboratory. The other two techniques have been more successful and have lasted longer: tinting and toning. Tinting is obtained by immerging the positive print into dye baths (the composition and proportions of which changed according with the colour) and homogeneously attaches over the entire film including the perforation area, darker parts remain black. Toning is a process obtained by immerging a positive print into a dye bath (that, also in this case, change according with the colour) where a chemical reaction replaces the neutral silver image with one consisting of coloured metal compounds. In toning the film base remain transparent and the gelatine is coloured. These three techniques could be combined as in the first and third samples below (fig. 2 and fig. 4).

Samples from French and Italian Silent Films

The frames selected for this research are from French and Italian films to have a very precise comparison with the colouring formulas in the manuals used in these areas. All the films stocks are 35mm nitrate base and, of course, positive prints.

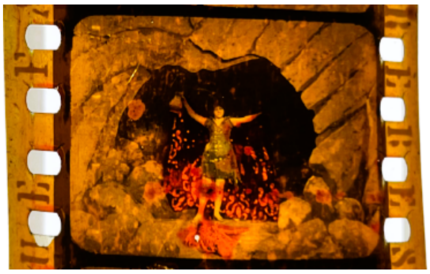

Fig. 2 – Film Pathé (1907 - 1909)

The first sample, figure 2, is a frame from an unidentified film Pathé (most likely of the series Scènes à trucs) printed on a Pathé film stock produced, according to the manufacturer's edge mark (Brown, 2020 ed.), between 1907 and 1909. The colour of the film was obtained combined two techniques: an orange / yellow tinting and a red pochoir on the woman figure, the smoke behind her and the skeleton on the ground.

Fig. 3 – Tinted samples

The first frame in figure 3, is an end title of Tiziano film printed on an unknown film stock (there is not edge marks or other signs for identifying the manufacturer). Tiziano film was a production company from Turin operating only for two years, 1920 and 1921, and because there is no photographic trace of previous perforation, the film was printed directly from the original negative. The colour of the frame is a red tinting.

The second frame is from an unidentified French film, also in this case the stock is unknown, datable post 1909 because the KS (Kodak standard) perforations introduced from that year. The photographic sign of perforation from previous film materials indicate that is not a first generation print but a following copy. The colour of the frame is a yellow tinting.

La bocca suggellata (Michele Malerba, 1920) is a film produced by Tornielli Film Torino. The frame, the third in figure 3, shows the title and some credits. Because there isn't an edge mark or a photographic trace of previous perforations, it was probably printed at the time of the first distribution of the film. The colour of the frame is a red tinting, slightly different, colder, form the one of Tiziano film.

Fig.4 – Tinted and toned Italian film.

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The last sample is a frame from an unidentified Italian film, probably a short documentary or a newsreel, printed on an unknown film stock, no photographic trace of a previous film materials. We can set this film in the first part of the1920’s. The colour of the film is a combination of two techniques: a light blue tinting and a blue toning.

Source of Formulas
The colour recipes use for comparing the results of spectroscopic analysis are from two manuals: Vittorio Mariani, *Guida pratica alla cinematografia* and *Le film vierge Pathé. Manuel de développement et de tirage*.

The Mariani manual was published in 1916 and embrace almost all the activities connected to the film production from the construction of the set and shooting to lab treatments and projection. When the film industry grew all these activities were separated in specific branch (as they still are today) but at the beginning of film history they were often integrate in one facility. The section thirteen is dedicated to film colourisation formulas for tinting and toning. *Le film vierge Pathé. Manuel de développement et de tirage* published in 1926, is a more specific manual, for the laboratory work and more detailed in the description of procedures for developing, printing and colouring film. The colourisation process is in the section ten dedicated to the development of positive prints. The manual dedicates a section to other colourization technique as, for example, the pre tinted film Pathé.

Both manuals collect recipes from earlier sources and fixed practices already in use in film laboratories.

Analytical Methods
The colour of the five frames was analyzed by different spectroscopic techniques with non-invasive and in some cases micro-invasive methods.

Raman spectroscopy was applied in micro mode and with low incident power to preserve the highly flammable cellulose nitrate film support. It is a non-invasive analysis based the inelastic scattering of radiation by the sample molecules and associated with molecular vibrations. For this reason, it is a technique that allows to univocally recognize the analysed compound. The micro-Raman spectra were acquired using a Jasco TRS 300 triple monochromator spectrometer, equipped with an Andor CCD detector and interfaced with an Olympus BH-2 microscope. A Cobolt Twist TM 25 laser with emission at 457 nm (blue) was used as excitation source. The spectral region 800-1800 cm^{-1} was considered.

To overcome the fluorescent emission, one of the biggest limitations in Raman effect that could hide the signals in the final spectrum, surface-enhanced Raman spectroscopy (SERS) was also used. It is a micro-invasive technique, in which the signal is amplified by the interaction between the analyte molecules and a nanostructured metal substrate. If a selected excitation wavelength that corresponds to the absorption band of the sample is used, a further amplification is observed due to the resonance effect. In this case a colloidal suspension of silver nanoparticles was used, prepared according to the Lee and Meisel procedure (Lee et al., 1982-86). The analysis was performed using a micro-Raman probe equipped with a notch filter and an Olympus 50X objective, connected to Lot-Oriel MS 125 spectrometer. The probe is also connected to a laser source with emission at 532 nm (green). To perform the analysis, a micro-sample was taken from the perforation area by scratching the film with a scalpel and the powder was placed on a glass slide with a drop of the solution containing the colloid and an aggregating agent (sodium perchlorate).

The absorption spectra in the UV-visible spectral region of the five frames were acquired as well. It is a non-invasive technique useful for the study of compounds that impart colour thanks to the presence of chromophore groups in the molecular structure. The analysis was conducted in transmission mode using a Jasco V-570 benchtop spectrometer with an acquisition range from 350 nm to 800 nm. Unlike the Raman spectrum, the absorption spectrum has broad bands and therefore is not specific for a given compound, but allows for some important considerations, such as the use of mixtures rather than pure compounds in the colour formulation.

Finally, to study the colour of the blue-toned film, Fourier transform infrared (FT-IR) Spectroscopy in specular reflection was used using a compact Alpha spectrometer from Bruker. The measurement was carried out on an area of approximately 6 mm in diameter on the emulsion side of the frame.

Results and Discussion

The identification of the compounds used for the tinting of the five frames was possible by comparing the spectroscopic data acquired using the techniques mentioned above with the bibliographic references and 19th-20th century filmography manual. An example of that is shown in figure 4.

Red tinting

The UV-visible spectrum obtained in transmission mode on the red frame from *La bocca suggellata* (fig. 3) is comparable with the spectrum of the red dye Eosin Y (Acid Red 87), a xanthene dye widely used for the red tinting (Mariani, 1916). The correct identification of this dye has been confirmed by Raman spectroscopy (λ_{exc}= 457 nm) (Saviello et al., 2018). The use of this dye for film tinting is documented in some cinematography manuals (Mariani, 1916) alone to obtain a pinkish dye or mixed with other compounds to obtain yellow-orange colours.
The red dye used for the tinting of the frame with the end title of Tiziano film (fig. 3) was identified by surface-enhanced Raman spectroscopy (SERS) as Ponceau 2R (Acid Red 26), that gave the film a fiery red colour. In film manuals (Pathè, 1926), there are references to the use of different types of Ponceau dyes in tinting formulas, in particular the use of ponceau 3R. However, it must be considered that from a chemical point of view the Ponceau 2R and Ponceau 3R dyes have the same molecular structure except for the presence of a methyl group and this difference is too subtle to be detectable by SERS analysis. Therefore, it cannot be excluded that the red dye in question is precisely the Ponceau 3R. In general, Ponceau dyes are synthetic azo dyes characterized by the presence, in the structure of the molecule, of a -N=N- double bond linked to two aryl substituents or their derivatives.

Yellow - orange tinting and pochoir

For the frame shown in figure 3 the use of an orange dye was at first hypothesized from the UV-visible spectrum despite the yellowish colour of the film. In fact, its absorption maximum is located at about 480 nm, while the yellow dyes normally used for tinting absorb at slightly lower wavelengths (AAT Bioquest, Inc., 2024).
The concrete assumptions about the nature of the dye used for the tinting were possible through the SERS technique which made it necessary to take a powder sample in the low perforation area. The obtained SERS spectrum shows clear analogies in the trend and intensity of the signals with a SERS spectrum of the Orange G dye (Acid Orange 10), a synthetic mono-azo dye attested for use in tinting formulations in several manuals. For example, Gregory in *Motion Picture Photography* (Gregory, 1927) registers a list of standard dyes which have been chosen as fulfilling the tinting conditions as nearly as possible and the Orange G is one of them for the “Cine Orange” tint. The use of this dye is also attested in the Agfa manual (Agfa, 1925) in the tinting formula n° 6 (fig. 5).

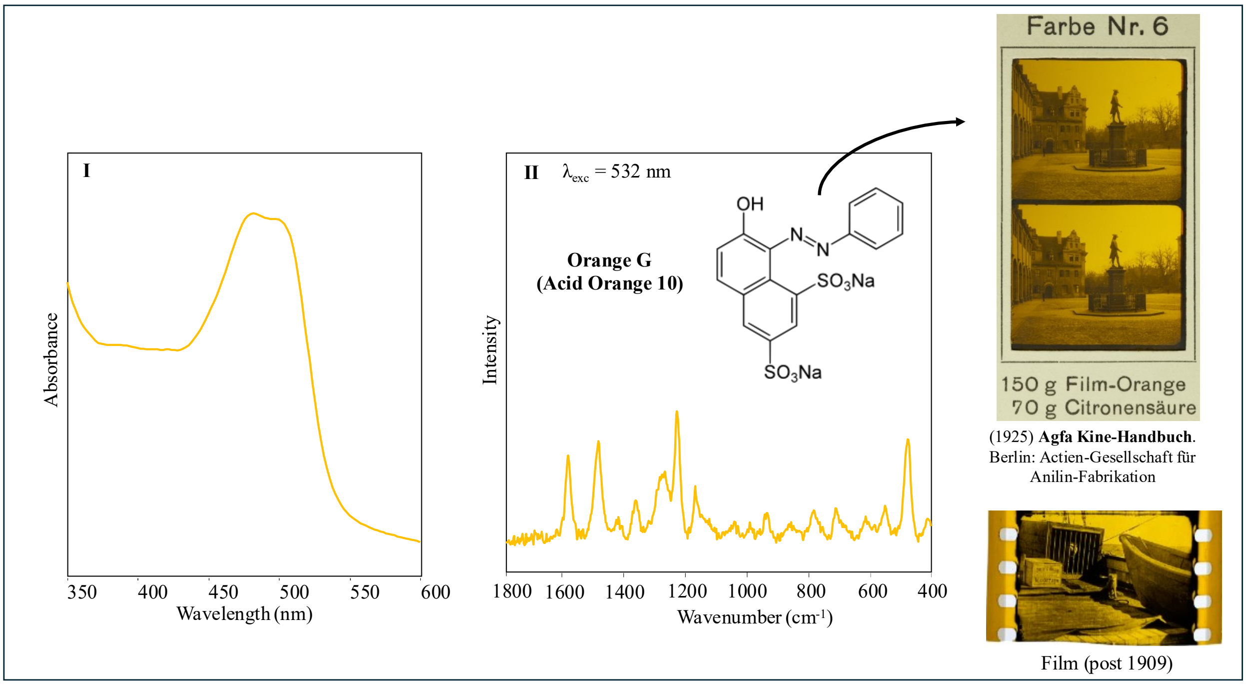

Fig. 5: UV-visible (I) and SERS spectrum (II) with identification of the dye in the sample with a yellow tinting (fig. 3).

The sample shown in figure 2, in addition to having a colouring given by the pochoir technique, has an orange/yellow tinting. Given the preciousness of the film fragment, no samples were taken from it but thanks to non-invasive techniques it was possible to hypothesize the nature of the orange dye. In the UV-visible absorption spectrum it is clearly observed that it is actually a mixture of two dyes due to the presence of two relative absorption maxima: tartrazine, a yellow dye, and eosin Y, a red dye already mentioned for the tinting of the sample in figure 4. Tartrazine is one of the oldest known members of the pyrazolone family of dyes (Hunger, 2003), i.e. molecules that present as central group a 5-membered heterocycle containing two adjacent nitrogen atoms. This mixture is cited in (Mariani, 1916) to obtain an orange tinting or yellow tinting, according to different proportions of the two dyes.

The identification of the dyes used in the pochoir for the red and green areas of the frame was however very complex, especially because the responses of the analyses were strongly influenced by the background response of the tinting mixture tartrazine + eosin Y and it was difficult to isolate the individual signals due only to the pochoir dyes. In the case of the red details, however, Raman spectroscopy (λ_{exc} = 785 nm) allowed to observe signals possibly attributable to a red dye of the rhodamine class.

<u>Blue toning</u>

The sample in figure 4 shows blue toning and also a light blue tinting has been hypothesized. The spectroscopic analyses performed on this frame do not seem however to support this hypothesis, especially due to the lack of Raman signals that can be assigned to an organic compound.
For the study of the colour due to toning, FT-IR spectroscopy proved useful, as the film spectrum shows a band at 2070 cm-1 attributable to the stretching vibration of the -C≡N-, which indicates the presence of cyanide compounds characteristic of the toning formulation.

Conclusions

The application of non-invasive and/or micro-invasive analytical methods to the study of the colour of motion picture films has allowed us to obtain some important information. First, for most of the samples, these methods have enabled us to uniquely identify the dye used in the tinting formulation, finding a direct correspondence with the historic manuals available in the literature. In cases where the dye has not been identified, because of the impossibility of taking a sample or due to the overlapping of tinting and pochoir, these techniques still allowed the identification of the chemical family to which the dye belongs.

In particular, micro-invasive methods have permitted us to confirm some hypotheses based on the results obtained by non-invasive ones, confirming the validity of these methods as well. These latter were fundamental in identifying the dye in a red frame and a dye mixture often used to obtain an orange tinting and in distinguishing the metal toning process from the tinting one.

The importance of the study and the identification of synthetic dyes used during the silent era is fundamental from the perspective of film conservation and restoration. In the context of the debate surrounding photochemical and digital restoration of audiovisual heritage, the results of these analyses could be as an important starting point for creating a database of technical data available to restorers to reestablish the film's original colour. In fact, from the spectroscopic data, it is possible to obtain the colorimetric coordinates, essential for digital restoration. Furthermore, due to the frequent lack of clear references in the literature, analyses of this kind help clarify the types of dyes used in historical cinematography enriching the documentation collected for a restoration project.

In conclusion, the results of these analysis can be another important source for the preparation a film restoration project in correlation and mutual confirmation with film materials, non film materials, archival and bibliographical documentations.

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Influence of the binder on the susceptibility of the painting irradiated with a nanosecond pulse Nd:YAG laser at 1064 nm.

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Abstract

This study is part of the vast panorama of laser applications for cleaning artworks with a particular focus on the application of a Nd:YAG laser working at 1064 nm to clean tempera and frescos paintings. Paintings mock-ups were prepared following traditional recipes with green earth, egyptian blue, cinnabar, chromium oxide, ultramarine blue and mars red. Before being irradiated with the laser, the samples soiled with soot were exposed to an artificial ageing in a climatic chamber with exposure to SO_2. For comparative purposes, pigment pellets and references paintings were also irradiated. Surfaces were analysed with stereomicroscopy and colour spectrophotometry for an estimation of physical changes. Moreover, chemical changes were evaluated by Fourier-transform infrared spectroscopy. As result, damage thresholds of paints were higher than those determined for their corresponding pellets. Thus, the binder has a protective character for the pigment. Cinnabar- and mars red-based paints were most sensitive under laser radiation leading colorimetric changes with low fluences, while blue and green paints were laser-resistant. The protective effect of the binder depends on the mineralogical composition of the pigment: cinnabar, mars red and ultramarine temperas showed higher resistance to laser radiation than their fresco counterparts, whereas for the rest of the pigments, the fresco paintings were more resistant. Regarding soiling cleaning, the irradiation with the painting damage thresholds provoked damages on the pictorial layer, so decrease the fluence was necessary, except for the red pigments with both binders. Although the cleaning was satisfactory at naked eye, soiling remain was detected in cavities by means of stereomicroscopy and FTIR.

Keywords: laser cleaning, pigment, soiling, fresco, tempera, conservation, egg yolk.

Introduction

Since 1970´s, in which a laser was used for the first time by Asmus to remove dark encrustations on Venetian marble (Asmus et al., 1973), laser ablation as a cleaning method of Cultural Heritage materials has been deeply investigated, mainly for stone (Fotakis et al., 2006; Pereira-Pardo and Korenberg, 2018, Zanini and Bartoli, 2018). Laser factors that mainly condition an effective cleaning of the stones without exerting harmful effects to the forming minerals are: the active medium, the wavelength, the pulse duration and the fluence. Then, in order to optimize the laser cleaning is necessary to determine, before cleaning the undesirable surficial deposit, the effect of the different factors in a step-by-step methodology: 1st to find the interaction of the available laser beams with the reference (without any undesirable substance) to determine the damage threshold; 2nd to determine the fluence necessary to extract the undesirable deposit and 3rd to optimize the laser parameters to extract the deposit on the artwork, avoiding damage. Although less research has been carried out in wall painting comparatively to stone, this step-by-step methodology must be considered to achieve a satisfactory cleaning, considering the compositional complexity of these paintings, specifically tempera wall paintings and fresco paintings. The former are made of an inorganic pigment (cinnabar, malachite, azurite, etc.) and an organic binder such as rabbit glue or egg yolk (Mayer, 1985). Usually, the paint is applied on a substrate of calcium carbonate formed as a result of the carbonation of

portlandite. In fresco painting, pigments are painted onto the outer layer of mortar when it is still wet. This enables the pigments to bond to the surface via a carbonation process, i.e., calcium hydroxide reacts with atmospheric CO_2 to form calcium carbonate.
Among the deterioration forms (EwaGlos, 2016), soiling composed of particulate matter, dirt and pollutants due to traffic emissions and industrial activities, is commonly found on wall paintings, when they are (semi-)exposed outdoors. The paintings components (pigment and binder) with different physical and chemical behaviours show different susceptibilities, making laser cleaning of wall paintings a real challenge.
Regarding the laser cleaning of wall paintings, scientific studies address the effect of different laser systems on pure pigments, simulated tempera mock-ups (using different binders) with/without an undesirable deposits (varnishes, artificial patinas, complex layers of polymers, etc.) or real tempera artwork (Castillejo et al., 2002, 2003; Bracco et al., 2003, Chappé et al., 2003; Oujja et al., 2003, 2013, Pouli et al., 2003, 2009; Andreotti et al., 2007, 2016; Camaiti et al., 2008; Siano et al., 2012).
Considering the cited scientific publications, it is necessary, to achieve a satisfactory cleaning of wall painting, firstly to determine the effect of the laser parameters on the painting components and the whole painting without the undesirable substances to determine the damage threshold. Secondly, the mineralogical composition of the pigment and the binder nature must be taken into account in order to understand the behaviour of the paintings under laser radiation.
This study, using a nanosecond (6 ns) pulsed Nd:YAG laser with a 10 Hz repetition rate working with a 1064 nm wavelength, aimed to identify: 1) damage thresholds for pigment and paint mock-ups, considering the effect of the binder (calcite and egg yolk) on the behaviour of the painting under laser irradiation and 2) the effect of the application of these damage thresholds on the soiled mock-ups to identify the role of the soiling-paint interaction on the cleaning effectiveness.

Material and methods

Samples preparation

The selected pigments (supplied by Kremer GmbH) are among the most popular colours in wall paintings, such as red, green and blue. Two pigments were chosen for each, one representing use from the earliest period (cinnabar, green earth and egyptian blue) and the other from modern production since the 18^{th} century (mars red, chromium green and ultramarine).
Pigment-only samples were made into 4 cm diameter aluminium moulds and compacted with a 30-tonne press. Regarding painting, the reproduction of fresco and tempera paintings were made following the Old Master recipes (Pozzo, 2009). Part of the painting samples were contaminated by soot collected from diesel engine car exhaust pipes. It was deposited on the mock-up surfaces before introducing them into a climatic chamber FITOCLIMA 300EDTU with gases exposure. Samples were exposed for 40 days under a relativity humidity of 80%, temperature of 18ºC and SO_2 concentration of 200 ppm.

Laser system

The laser applied was a Q-Switched (QS) Quanta Ray INDI-series operated at 1064 nm (IR radiation) with a pulse duration of 6 ns and a 10 Hz repetition rate. To improve focalization, a convergent lens with a focal length dependent on the fluence required for each sample was used.
The methodological approach conducted (Fig 1) was based on: firstly, 0.3cmx0.3cm square tests were done on the periphery of each sample to look for the conditions at which minimum damage began to appear. Once identified, this fluence (identified as D) was used to do a 1.2cmx1cm square in the top left side of the tablet (Fig 1.1). Then, to identify the damage threshold, two more squares (1.2cmx1cm) were made decreasing the fluence identified as D: reduction of 10% (identified as D-10% area in the top right of the tablet) and 40% (identified as D-40% area in the down left of the tablet). If the -10% area had no visible damage, it was selected as the damage threshold (Th_P). If -10% showed visible damage and the - 40% did not, this was selected as the damage threshold (Th_P). Finally, other square

(1.2cmx1cm) was done increasing D fluence by 40% to ensure a clear damage on the sample (identified as D+40% area in the down right of the tablet).
Secondly, the fluence identified as threshold fluence-Th_P- (-10% or -40%) was used to perform a 1,2cmx1cm square in the paintings (Th_P, Fig 1.2). If physical changes occurred in the paint (mainly darkening or extraction), the fluence was decreased to find the damage fluence of the paints (Th_{EY}/Th_F). The fluence was then increased to find the surface damage fluence (F_{dam}).
Finally, the fluence identified as the damage threshold (Th_{EY}/Th_F) of the paintings was applied to the soiled samples (Fig 1.3). If this fluence was not sufficient to clean the paint or it allowed the removal of the soiling but also the paint layer, it was raised or lowered respectively to achieve the appropriate cleaning playing with the number of scans (1 or 2 scans) to achieve a gradual cleaning.

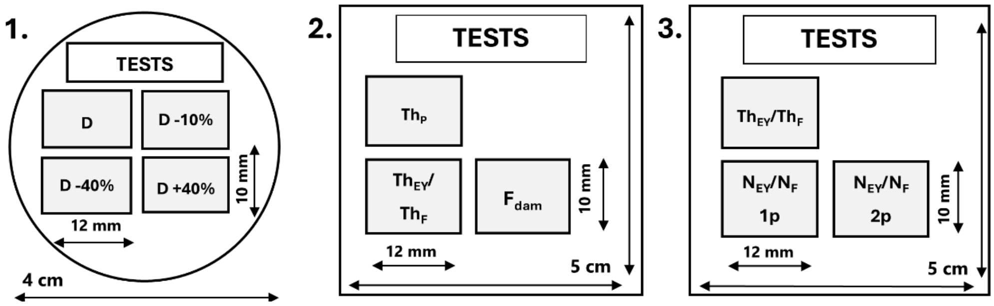

Fig 1 - Methodological approach following in the research based on the application of the laser Nd:YAG at 1064 nm. 1. Pigment tablet. 2. Painting without an undesirable substance and 3. Soiled painting.

Analytical techniques

The following techniques were applied in the samples before and after the laser irradiation:

- A stereomicroscope (SMZ800 Nikon) was used to detect physical changes (textural, structural and colorimetric features) of the samples.
- A Minolta CM-700d spectrophotometer was used to characterise the colour of each pigment tablet and each irradiated area. Measurements were taken in the CIELAB and CIELCH colour spaces. L* represents lightness, varying from 0 (black) to 100 (white), a* is a colour position between red (+ a*) and green (- a*) and b* is a colour coordinate between yellow (+ b*) and blue (- b*). C^*_{ab} is the chroma or saturation and *h* represents the hue. Measurements were made in specular component excluded (SCE) mode, for a spot diameter of 3 mm, using a D65 illuminant and an observer angle of 10º. Five measurements were made for each area (reference and irradiated) of each sample. Taking the colour of the tablets before irradiation as reference, the ΔL^*, Δa^*, Δb^*, ΔC^*_{ab} and ΔH^* differences and the colour difference (ΔE^*_{ab}) were calculated following CIE (2007). Values of ΔE^*_{ab} were considered on the basis of the ability to see differences of an unexperienced observer (Mokrzycki & Tatol, 2011).
- Molecular changes in the paintings and soiling remain were determined by a portable Fourier-transform infrared spectroscopy (FTIR) 4300 Agilent with an Attenuated Total Reflectance (ATR) system.

Results and Discussion

The determination of the threshold fluence for the pigments in tablets allowed to establish their susceptibility at the irradiation with the laser QS Nd:YAG operating at 1064 nm. The mineralogical composition influences this interaction the most. Indeed, the more resistant materials, i.e. those to which a higher fluence (Th_P in Tab 1) was applied, were found to be silicate pigments, such us green earth, egyptian blue and ultramarine. Disregarding cinnabar, which had the worst performance, pigments consisting of oxides were found to be more sensitive: chrome green and mars red. The pigment that reacted worst to laser was cinnabar (a sulphide), because at low fluences (<0.11 J/cm^2), clear blackening was already observed. Chappé et al. (2003) reported that if a pigment shows a reaction to irradiation with an energy density below 0.04 J/cm^2, it is defined as 'unsuitable' for laser cleaning. In the present work, however, it was possible to apply a fluence of 0.04 J/cm^2 and obtain a ΔE^*_{ab}=1.37 CIELAB units (Fig 2.CI). The fluences determined were confirmed to be the damage threshold fluences (Th_P) also by means of the ΔE^*_{ab}, which was below 3.5 u. CIELAB, a threshold value according to which an inexperienced eye notices clear differences in colour (Mokrzycki & Tatol, 2011). Only for ultramarine (Fig 2.UL) the ΔE^*_{ab}=4.83 u. CIELAB was higher than 3.5 u. CIELAB, because it was influenced by the L* component, which can be associated with roughness parameters (López , et al., 2018).

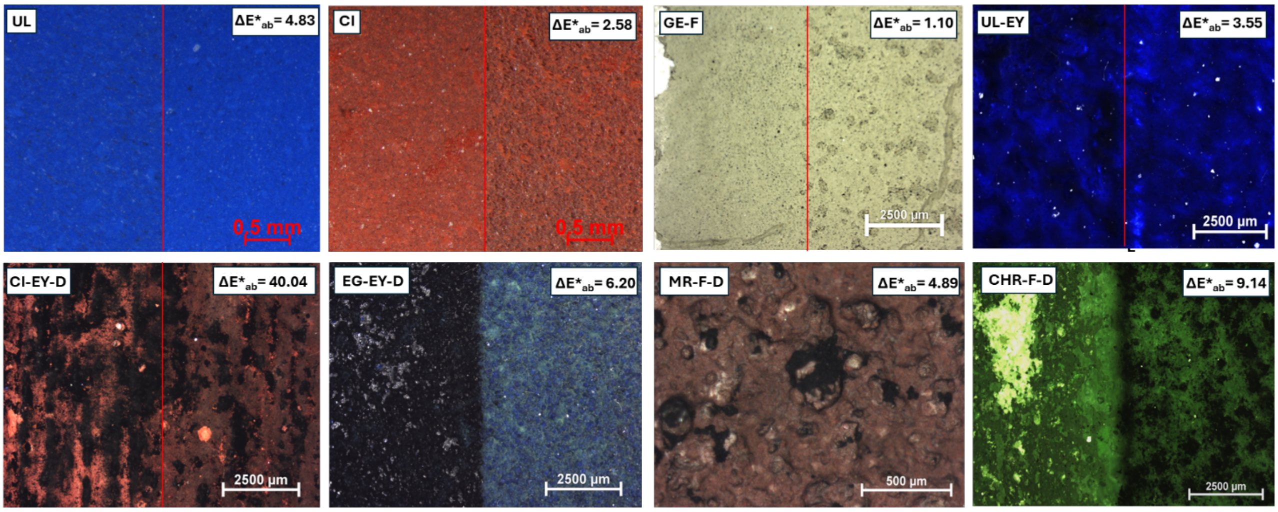

Fig 2-Micrographs of some of the samples used in this research. UL: ultramarine; CI: cinnabar; GE: green earth; EG: egyptian blue; MR: mars red; CHR: chromium oxide; EY: egg yolk; F: fresco; D: diesel soot. ΔE^*_{ab} (CIELAB units) is depicted for each treated surface.

For paintings, with most of the pigments, fluence increases, comparatively to pigment tablets, were required to reach the damage threshold (Th_F/Th_{EY}, tab 1), except for cinnabar and green earth with egg yolk. This was assigned to the protective character on the pigment by the binder, as confirmed by Schnell et al. (2006), applying a Nd:YAG laser at 1064 nm on pigment-only tablets and on paints with linseed oil, casein, gum arabic and lime. In fresco painting, through the carbonation of calcite, the pigment is incorporated into the *intonaco*. As a result of this process, the pigment's resistance seemed to be improved. The resulting calcite after carbonation had a whitish hue that caused low absorption of the laser beam due to its reflection (Cooper, 1998). This characteristic was evident in the two green pigment- and in the egyptian blue-fresco paintings (Fig 2.GE-F). Analogous process happened in tempera painting where egg yolk formed a protective film around the pigment. This protection factor occurred in the mars red and both blue pigments in tempera paints. Concerning ultramarine (Fig 2.UL-EY), tempera paint showed a ΔE^*_{ab}>3.5 u. CIELAB, which could be related to binder degradation (Oujja, et al, 2010) . It will be a priority of future studies to investigate this further.

In the case of improper use of the laser with fluences greater than the threshold fluence ($F_{dam\text{-}F}$ and $F_{dam\text{-}EY}$; Fig 1.2): it was possible to ascertain chromatic changes and paint extraction. Specifically, paintings with red pigments turn to black (Fig 2.MA-F-D), while those with egyptian blue with both binders and green earth in tempera painting altered to lighter colours tending to yellow according to positive values of the b* coordinate.

FTIR allowed to confirm the extraction of the surface carbonation layer after irradiation, particularly in the green earth fresco painting (Fig 3), in which a change in the relative intensity, with a decrease of the 997 cm^{-1} band of the pigment and the increment of 870 cm^{-1} band assigned to C=O of the

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calcium carbonate was evident (Fig 3.1). In the tempera paintings (Fig 3.2), changes in the intensity relations occur between the decreasing of the band at 1745 cm^{-1} assigned to carbonyl functional groups of triglycerides and the increasing of the band assigned to C=O stretching from amide I (protein) at 1654 cm^{-1}, which could be due to protein denaturation at 60 – 75 °C (Blume, et al., 2015).

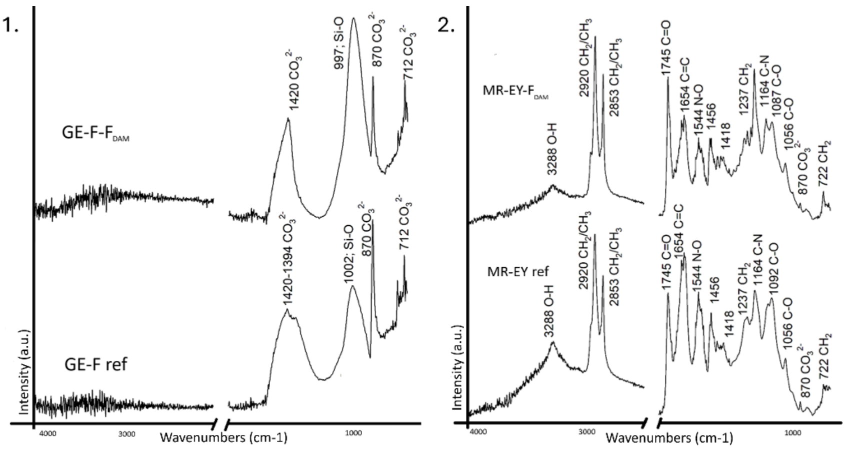

Fig 3 - FTIR spectra of some of the paintings before (ref) and after (F_{DAM}) laser irradiation. 1: green earth-based fresco paintings, 2: mars red-based egg yolk paintings.

Tab 1 - Threshold fluence (J/cm^2) of pigments (Th_P) and paintings (Th_F/Th_{EY}) with ΔE^*_{ab} (CIELAB units)

Pigments	Th_P (J/cm^2)	Th_{EY} (J/cm^2)	Th_F (J/cm^2)
Cinnabar	0.04 ΔE^*_{ab}=1.37	0.04 ΔE^*_{ab} =4.37	0.02 ΔE^*_{ab} =2.51
Mars red	0.15 ΔE^*_{ab} =1.89	0.27 ΔE^*_{ab} =1.20	0.18 ΔE^*_{ab} =1.10
Green earth	1.90 ΔE^*_{ab} =3.28	1.36 ΔE^*_{ab} =2.48	2.35 ΔE^*_{ab} =1.24
Chromium green	0.31 ΔE^*_{ab} =1.46	0.36 ΔE^*_{ab} =0.54	0.97 ΔE^*_{ab} =4.31
Egyptian blue	0.81 ΔE^*_{ab} =3.39	1.94 ΔE^*_{ab} =1.96	2.74 ΔE=2.80
Ultramar	1.74 ΔE^*_{ab} =4.83	2.61 ΔE^*_{ab} =3.55	2.48 ΔE^*_{ab} =2.95

The application of the threshold fluences for each painting (Th_F/Th_{EY}) to remove the soiling produced different effects which can be categorised according to two criteria: i) soiling removal and ii) paint damage.

In terms of soiling removal, for cinnabar-based paintings with both binders and mars red-based fresco, it was necessary to increase the fluence to achieve the necessary fluence for cleaning (N_F/N_{EY}). However, in the cinnabar paintings it was not possible to remove soiling, despite the fluence increase, since remains can still be identified using stereomicroscopy (Fig 2.CI-EY-D) and FTIR. In mars red-based fresco, soiling was removed superficially but remained in the cavities (Fig 2.MR-F-D).

Regarding damage, threshold fluences detected for paintings induced chromatic changes and pictorial layer extraction. With fluences between 0.3 and 2 J/cm^2, chromatic changes and minimal extraction were visible in tempera paintings with green earth and egyptian blue and in chromium green-based fresco (Fig 2.CHR-F-D), while in tempera paintings containing chromium oxide, only minimal

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ablation of the paint was visible in those areas where greater roughness was present. With fluences above 2 J/cm^2, complete extraction of the paint layer was caused in both paintings containing artificial ultramarine and in the green earth and egyptian blue-based frescos. Considering the literature (Cooper, 1998), the extraction of the paint was the result of photothermal ablation with fluences above the threshold, which caused an explosive vaporisation favoured by the soot, i.e. a perfectly absorbent layer of contamination that promoted a sudden temperature rise, generating sufficient forces to overcome the particle's adherence to the surface. However, further studies are needed to investigate the temperatures reached.
During the cleaning, the binder seemed to exert a greater influence than the pigment mineralogy in the interaction paintings-laser. In fact, it was possible to apply higher fluences in the tempera paintings for all paintings with exception of those with chrome green and egyptian blue, which allowed higher fluences with fresco painting. The only pigment for which mineralogy continued to be of considerable importance was cinnabar, which was characterised by a strong sensitivity to laser interaction (Fig 2.CI-EY-D).
The cleaning experienced critical issues in the egyptian blue with both binders, because from the colorimetric analysis, b* coordinate showed more positive values towards yellow tones in comparison to the reference (Fig 2.EG-EY-D). This yellowing could be due to the light scattering in a thin absorbent layer and the surface roughness as was reported by Vergès-Belmin and Dignard (2003). However, the chromatic changes because of accelerated ageing in the climate chamber cannot be dismissed. So further studies are needed. In general terms, in those samples with satisfactory levels of superficial cleaning, remains found in cavities can jeopardize the cleaning effectiveness, specifically in the mars red (Fig 2.MR-F-D) and chromium green tempera paintings. FTIR spectra revealed (Fig 4) the conspicuous removal of soiling, due to an intensity increase in the 1750- 1200 cm^{-1} (bands assigned to the protein binder) and a decrease at 1450 cm^{-1} (soot). The paintings in which the cleaning was considered satisfactory by stereomicroscopy and FTIR were those with ultramarine blue and green earth with both binders and the chromium green-based paintings.
The fluence required for cleaning was applied in two areas with one (1p) and two (2p) (Fig 1.3) laser scans to allow the operator to proceed gradually with the soiling removal avoiding damages. However, not for all the paintings was the two-scans square chosen. Specifically for the cinnabar-based paintings and the fresco with the red of mars, 1p squares were chosen because colour changes in the 2p squares were detected, specifically turning to darker shades, with a decrease in the L* coordinate. It should be noted that the L* was also influenced by the permanence of soiling on the surface. In order to be more conservative, 1p square was also chosen for the tempera paintings with the blue pigments, because the 2p square in egyptian blue tempera showed yellowing and the 2p squares in ultramarine tempera a slight discolouration, which needs further investigation.

Tab -2- Necessary fluence for cleaning (N_F and N_{EY}) compared with threshold fluence (Th_F and Th_{EY}) of the paintings. Under each fluence it is described the effect of the laser.

Pigments	Tempera (EY)			Fresco (F)		
	Th_{EY} (J/cm^2)	N_{EY} (J/cm^2)		Th_F (J/cm^2)	N_F (J/cm^2)	
Cinnabar	0.4		0.095	0.02		0.087
	no effects on soot or paint	1p	darkening paint & soot remains	no effects on soot or paint	1p	darkening paint & soot remains
Mars red	0.27		0.27	0.19		0.25
	remains a lor of soot	2p	some soot remains	no effects on soot or paint	1p	some soot remains
Green earth	1.36		0.6	2.35		0.24
	slight painting film extraction	2p	no soot	painting film extraction	2p	no soot

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Chromium green	0.36 slight painting film extraction	2p	0.23 some soot remains	0.97 painting film extraction	2p	0.28 no soot
Egyptian blue	1.94 chromatic change & painting film extraction	1p	0.44 no soot & slight yellowing	2.74 painting film extraction	2p	0.8 no soot & slight yellowing
Ultramarine	2.61 painting film extraction	1p	0.44 no soot	2.48 painting film extraction	2p	0.3 no soot

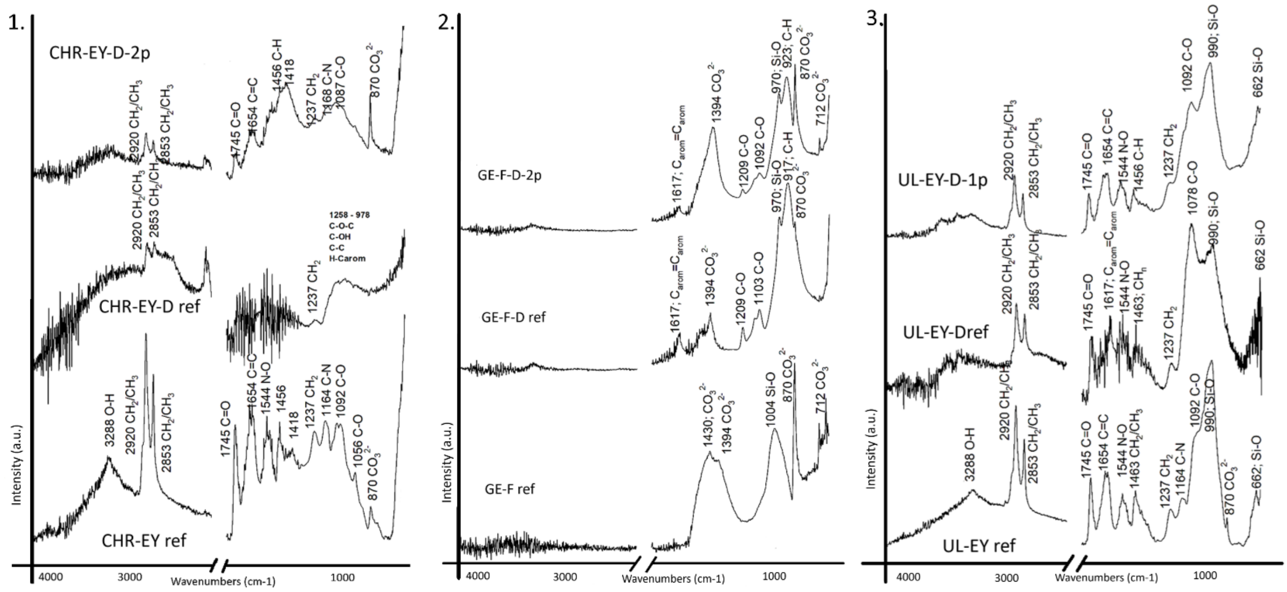

Fig 4 - FTIR spectra of some of the soiled paintings exposed to laser irradiation. 1: chromium oxide-based egg yolk paintings; 2: green earth-based fresco paintings, 3: ultramarine-based egg yolk paintings.

Conclusions

A Nd:YAG working at 1064 nm was applied to remove an artificial soling on fresco and tempera paintings with blue, green or red pigments with different composition. The damage thresholds for the pigment tablets and the paintings considering the effect of the binder (calcite or egg yolk) were determined previously to the cleaning of the soiled mock-ups. The binder does have a protective character for the pigment. Cinnabar- and mars red-based paints were most sensitive under laser radiation leading colorimetric changes with low fluences, while blue and green paints were more laser-resistant. The protective effect of the binder depends on the mineralogical composition of the pigment. In general terms, the paint damage threshold irradiation to the soiled surfaces provoked damages on the pictorial layer, so in order to clean, a decrease of the fluence was necessary achiving satisfactory cleaning.

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Visible-induced infrared luminescence (VIL) with monochromatic visible excitation: a preliminary look into various artistic materials and possible future perspectives

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Abstract

Visible-induced infrared luminescence (VIL) has become a key tool in the cultural heritage field to detect and map the distribution of Egyptian blue on objects of archaeological and artistic significance. Nevertheless, other ancient (Han blue and Han violet) and modern (cadmium red, orange, and yellow) pigments also yield luminescence in the infrared (IR) range when stimulated by visible light. Not all wavelengths of the visible spectrum, however, contribute equally to the excitation of pigments and dyes. For instance, red light (630 nm) is known to induce strong luminescence in Egyptian blue, while green (520 nm) and blue (430 nm) wavelengths appear to stimulate this type of phenomenon to a significantly lesser extent. On the other hand, cadmium red is most excited by green light, while blue and red excitation prompts progressively weaker responses. A series of multiband imaging campaigns recently conducted at the CCR "La Venaria Reale" on ancient, modern, and contemporary works of art, as well as on paint mock-ups, featured VIL with monochromatic UV, blue, green, and red (450nm, 520nm, 630nm) excitation. These techniques, respectively referred to as UVIL, BIL, GIL, and RIL for the purposes of this contribution, revealed how other pigments, in addition to those mentioned above, emit infrared luminescence to various extents depending on the exact wavelength used for excitation. For instance, cobalt-, bismuth- and barite-containing yellows show stronger luminescence in GIL images, while orpiment and realgar provide more intense responses using BIL and GIL. Various types of lake pigments also yield different luminescence when excited with blue, green, or red light. Other luminescent materials were detected in plastic objects and in some pen and marker inks. Moreover, initial testing highlighted that binding media may also contribute to IR luminescence: linseed oil was found to enhance the response of certain pigments, while this does not seem to apply to polyvinyl acetate. In the near future, these preliminary observations will be corroborated by systematic studies on IR luminescence induced by monochromatic visible light in an attempt to further refine the tools currently available for materials identification and the evaluation of degradation processes.

Keywords: VIL, monochromatic light, artistic materials, pigments, binders

Introduction

Non-invasive analyses are becoming more and more important in the field of conservation. Multispectral imaging is one of the most common analyses (Poldi and Villa, 2006; J. Dyer *et al*. 2013; P.A.M. Triolo, 2019). It provides immediately qualitative information about the whole surface of the analyzed object. UV luminescence as well as IR reflectography are largely used to map different materials and pigments and to detect degradations. VIL technique has become more and more diffused after its introduction as tool to detect Egyptian blue on objects of archaeological and artistic significance. Other famous pigments detected by VIL are Han blue, Han violet and cadmium-based pigments (Verri, 2016). Nevertheless, there are other material, pigments, dyes and binders that are detectable with VIL technique. Previous studies on VIL with monochromatic visible excitation pointed out the behaviors VIL of barium sulphate and lead white, linseed oil, safflower dye or sandal wood among others (Daveri *et al*., 2016; Salvini, 2022). A series of multiband imaging campaign recently conducted at the CCR "La Venaria Reale" on ancient, modern, and contemporary works of art, as well as on paint mock-ups revealed that other pigments, especially organic and synthetic ones, and also dyes emit luminescence in the IR region under monochromatic excitation.

Materials and methods

All the photographs were taken with a Nikon Z7 II Mirrorless Full Spectrum camera, modified to extend its spectral sensitivity in the 350-1000-nm range, equipped with a complementary metal oxide semiconductor (CMOS) silicon sensor and providing a resolution of 8256 x 5504 pixels.

Visible diffuse light photography: lighting was achieved by placing two Elinchrom RX 1200 flashes to the right and left of the object, at an angle of approximately 45° to the normal to the surface, and with the aid of softboxes. Camera was equipped with a UV-IR Cut and BG40 filters. Image processing, carried out by means of Adobe Lightroom and Adobe Photoshop, included a color correction conducted by inserting a 24-color X-Rite ColorChecker Classic reference in the field of view.

Ultraviolet-induced visible fluorescence (UVF): lighting of the object was achieved by means of two continuous 5W LED UV lamps with emission peak at 365 nm. Camera was equipped with UV-IR Cut and BG40 filters. Image processing, carried out by means of Adobe Lightroom and Adobe Photoshop was conducted by inserting non-fluorescing spectroscopic references in the field of view.

UV/Visible induced luminescence VIL (UVIL - BIL – GIL – RIL): lighting of the object was achieved by means of two continuous LED UV (peak 365nm for UVIL), blue (peak 450nm for BIL), green (peak 520nm for GIL) and red (peak 630nm for RIL) light source (Figure N.1). Camera was equipped with an IR 850 filter. Image processing, carried out by means of Adobe Lightroom and Adobe Photoshop software, included a color correction conducted by inserting gypsum reference for the evaluation and reduction of the reflected light component, and an Egyptian blue reference (Kremer Pigmente n. 10060) in the field of view.

VIL false color: false color images were obtained in the RGB color space of Adobe Photoshop by using one reflection images acquired in the visible and one VIL images (UVIL, BIL, GIL, RIL). In particular, the green (G) and red (R) components of the visible image are transferred into the blue (B) and green (G) channels, while the red (R) component is replaced with the VIL image. This methodology yields false color images of the VIL-R-G (RGB) type.

Panels: four panels of pictorial mockups were designed to simulate the main artistic techniques from Antiquity to Contemporary art. They are the same panels used in a previous study performed in CCR La Venaria Reale (T. Cavaleri *et al.*, 2017). Panels were previously treated with a glue-based solution and prepared with *stucco* (rabbit skin glue and gypsum). Mockups were prepared with inorganic pigments and natural and synthetic dyes mixed in different binders (Arabic gum, egg yolk, linseed oil and PVAc) and with two different varnishes (acrylic and mastice). Panel 1 represents the ancient age palette, Panel 2 the medieval one, Panel 3 exhibits the modern and contemporary palette while Panel 4 shows different dyes.

Case studies: VIL test were performed also on works of art, from private and public collections, gone under conservation treatment in the conservation lab of CCR La Venaria Reale and on other mock-ups created to test conservation materials and practices.

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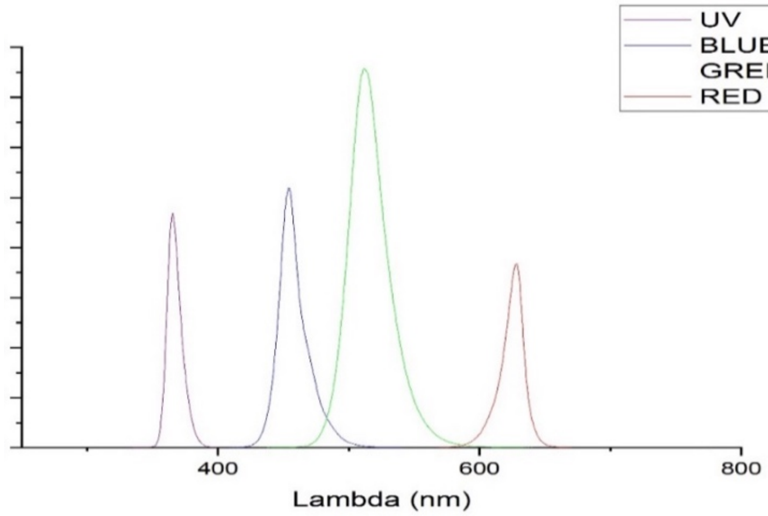


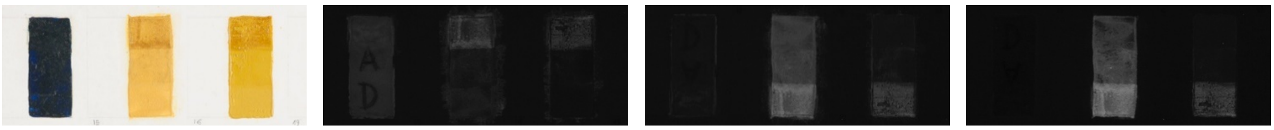
Fig. 6 – Emission spectrum of LED lights source used for VIL acquisition

Data collection and discussion

Panels – Mock-up

Panel 1 – Ancient Palette, Arabic gum and egg yolk binders: UVIL analysis shows the typical response of Egyptian blue (PB31), Han blue and Han purple. Egyptian blue in egg yolk has a stronger luminescence than in Arabic gum one. On the contrary, Han purple in Arabic gum provides a brighter luminescence than egg yolk. BIL technique presents the same trend for these three pigments. A weak luminescence appears for Garanza lacquer (NR9) and Brazilian wood (NR24) in egg yolk and for orpiment and realgar, in both Arabic gum and egg yolk, but only when varnished with mastic gum. GIL has the same trend of BIL. Garanza lacquer and Brazilian wood show a little fluorescence also in Arabic gum binder. Even RIL exhibits the same luminescence for all the cited pigments. Brazilian wood slightly increases while Garanza lacquer decreases.

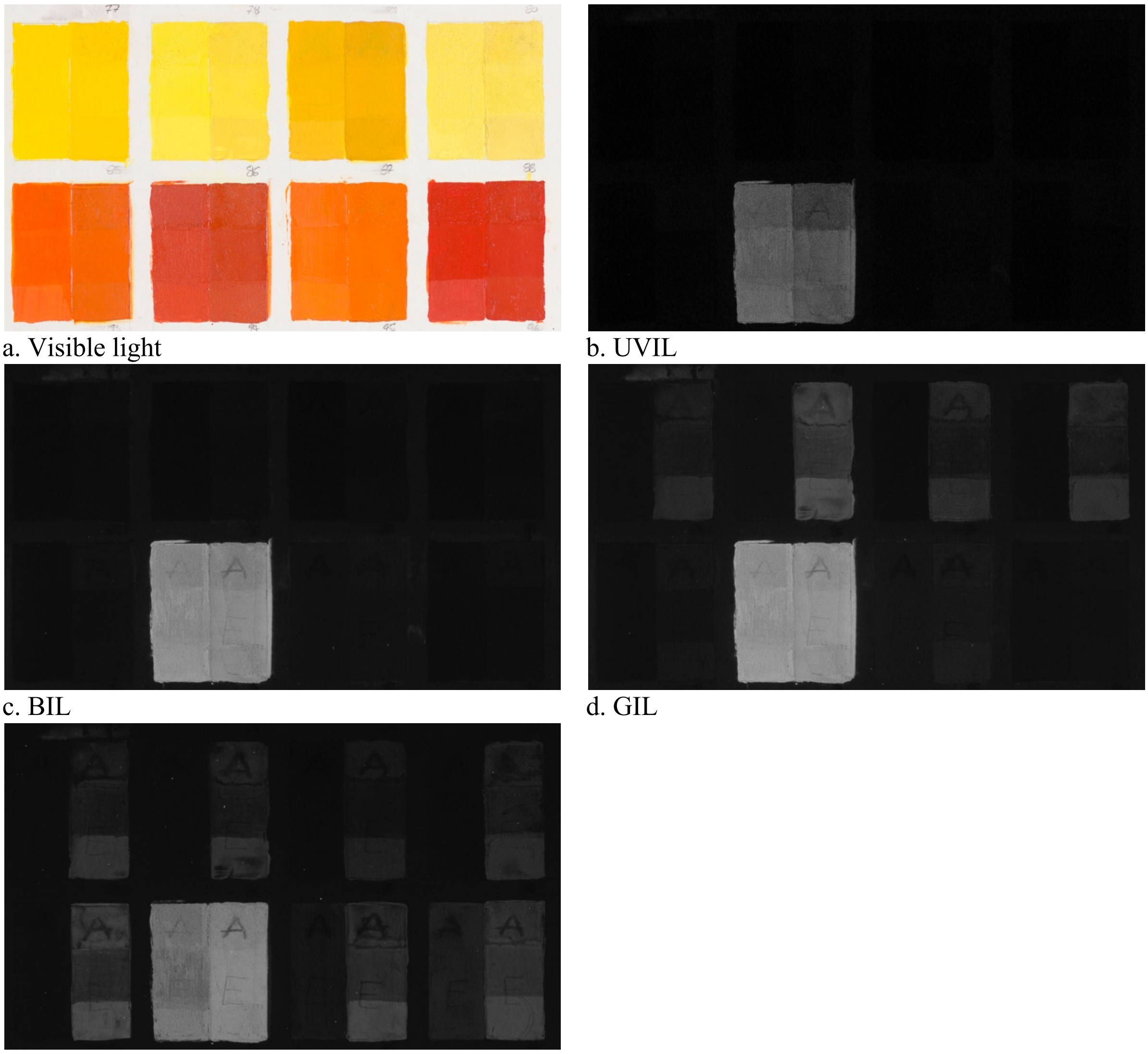
Panel 2 – Medieval palette, egg yolk and linseed oil binders: Barium sulphate is the only pigment that show luminescence with egg yolk and linseed oil in UVIL technique. Lead white (PW1), calcium carbonate and Garanza lacquer (NR9), also in combination with cinnabar (PR106), show a weak luminescence bonded with linseed oil. BIL shows a similar luminescence for lead white, calcium carbonate, and Garanza lacquer in linseed oil. Barium sulphate has a luminescence for oil, but not for egg yolk. Giallorino type I and ultramarine blue (PB29) in linseed oil become a little luminescent from UVIL to BIL, while Smaltino (PB32), Orpiment (PY39) and Realgar (PY39) gets a brighter fluorescence. GIL response is like BIL one even if there's a stronger response from orpiment and a weaker one from lead white. With RIL technique orpiment has the only strong response while Realgar has a lower one (Figure N.2). Other pigments don't exhibit luminescence.



a. Visible light b. BIL c. GIL d. RIL

Fig. 7 – Detail from Panel 2, from left to right Smaltino, Orpiment and Realgar in linseed oil

Panel 3 – Modern and contemporary palette, linseed oil and PVAc binders: UVIL brings a strong luminescence from cadmium-based pigments (yellow, orange, red and green). Strong luminescence is also from Iwa Enogh Iwabeni (Kremer 15222, that contains cadmium) and Paliogen orange (PR179). Other Iwa Enogh pigments with linseed oil show a weak luminescence. Zinc oxide (PW4), Lead white (PW1) just in linseed oil, Titanium orange (PBr24) and yellow sun gold studio pigment (mix of PY74, PBr24 and PW6) have a similar weak luminescence. A feeble one is also from Thioindigo (Kremer 23700), fluorescent blue pigment (Kremer 56050) and permanent green (mix of PB15:28, PG7:17, PW7). BIL displays a stronger fluorescence for almost all the cited pigments. White pigments (lead white, lithopone, titanium white, zinc oxide, zinc sulphide) emit luminescence only with linseed oil as binder. Cobalt blue (PB28) and Barite yellow (Kremer 43940) start to emit a faint, but visible luminescence in linseed oil. GIL technique manifests the same trend of BIL even if cadmium green and cadmium yellow slightly decrease their luminescence. Almost all yellow pigments (permanent yellow PY154, brilliant yellow PY74, studio yellow PY3, cobalt yellow PY40 and bismuth yellow PY184) begin to show fluorescence in linseed oil (Figure N.3). RIL points out some differences. White pigments and cadmium yellow, orange and red reduce their luminescence, cadmium green and Iwa Enogh pigments lose it completely while cited yellow pigments keep their one. Paliotol Orange, Isoindiol orange (PO61) and Ingarzin pigments (PR254, PR255) begin to emit a moderate luminescence.



a. Visible light
b. UVIL
c. BIL
d. GIL
e. RIL

Fig. 8 – Detail from Panel 3, from left to right at the top Brilliant yellow PY74, Studio yellow PY3, cobalt yellow PY40 and bismuth yellow PY184; at the bottom Paliotol orange, Paliogen orange PR179, Ingarzin orange, Isoindol orange PO61. For each pigments: left column is in PVAc binder, right column in linseed oil binder

Panel 4 – Natural and synthetic dyes, Arabic gum, linseed oil and PVAc binders: Permanent red (PR177, Anthraquinone) gives the most intensive luminescence under UVIL. Quinacridone pink

(PV19), Dioxazine Violet (PV37), Garanza lacquer (NR9) and Alizarina violet have a less bright luminescence while Turmeric dye has a powerless one. BIL technique confirms fluorescence for all the cited dyes. Other dyes in linseed oil like Grain d'Avignon (NY13), Still de Grain (NY13), sandal wood (NR22) and ortisca emit a little luminescence. Gutta gum (NY24) and Bristol Yellow start to emit fluorescence with GIL, while the response for other dyes is very similar to BIL one. With RIL technique the luminescence of almost all cited dyes decreases. Otherwise, Dragoon's blood (NR31), Studio red (Heliocrome red, PR3) and permanent red (Naptholo AS, PR9) gets a poor, but visible luminescence.

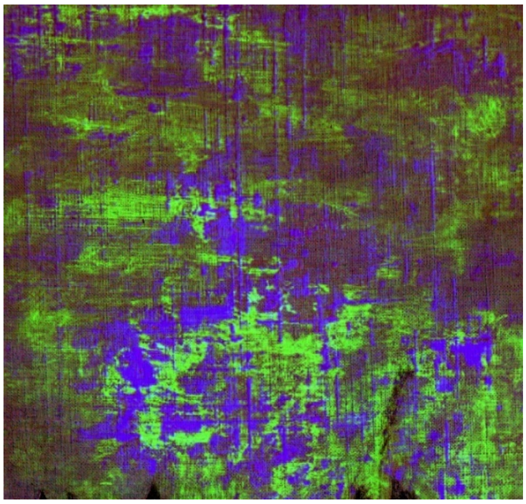
Case Studies

The first case study shows the use of different VIL to detect and map two different areas in the sky of a modern oil painting on canvas. UVIL shows complementary area of BIL and GIL. False colour images, obtained starting from UVIL and BIL, can help to better visualize the distribution of the two different pigments (Figure N.4). XRF analysis suggests that UVIL could indicate the presence of Titanium Dioxide in form of Rutile while BIL and GIL show another white pigment.

a. Visible light

b. UVIL false colour

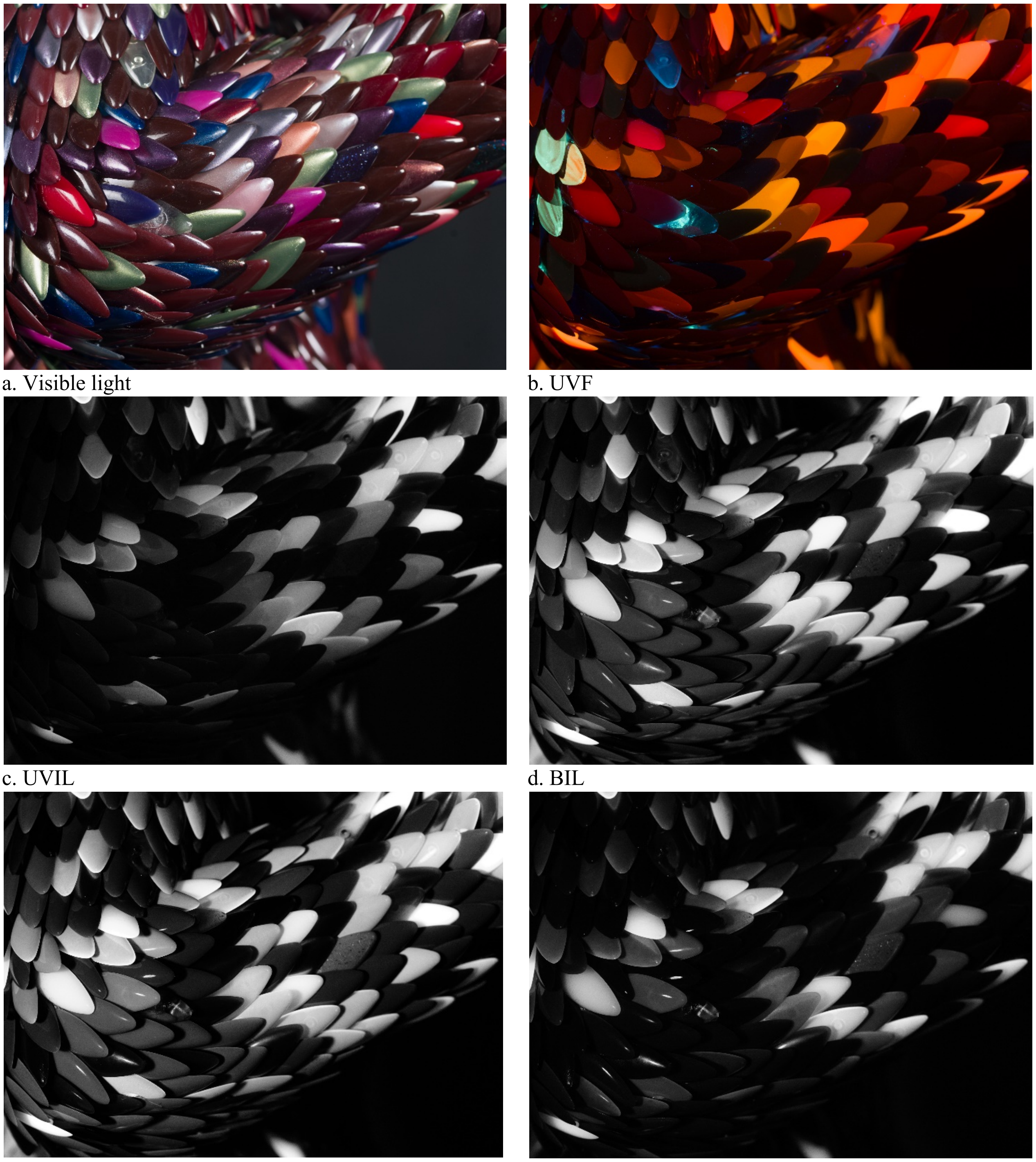
c. BIL false colour



d. UVIL-BIL-R false colour

Fig. 9 – Particular of the sky of a modern oil painting on canvas; a. Visible lights; b. UVIL false colour; c. BIL false colour; d. False colour RGB image in which B channel contains UVIL, G channel contains BIL and R channel is R channel from visible light image. This false colour image show easily the spatial distribution of pigments luminescent under UV light (Blue) and pigments luminescent under blue lights (green).

Another case study is a contemporary plastic sculpture from a private collection. The female body of the sculpture is composed by plastic "nails" of different colours. Some "nails" seem similar under visible lights, but they show different behaviours with UVIL, BIL, GIL and RIL technique. Comparison with UVF image suggests that some luminescence produced by UV light continue from visible to IR region while some emit just in visible region. Furthermore, BIL and GIL produce similar luminescence while RIL present less luminescent nails. The confrontation of the luminescent behaviour could identify different dyes used in plastic objects. (Figure N.5).



a. Visible light b. UVF
c. UVIL d. BIL
e. GIL f. RIL

Fig. 10 – Detail from *Venere con mela*, Enrica Borghi

Figure N.6 shows two mock-ups with and acrylic layer of, respectively, red and yellow pigment on a canvas primed with a white ground. Painting layers are covered by artificial soil. UVIL suggested the presence of Titanium Dioxide in form of rutile in the ground layer, confirmed by FORS analysis. BIL

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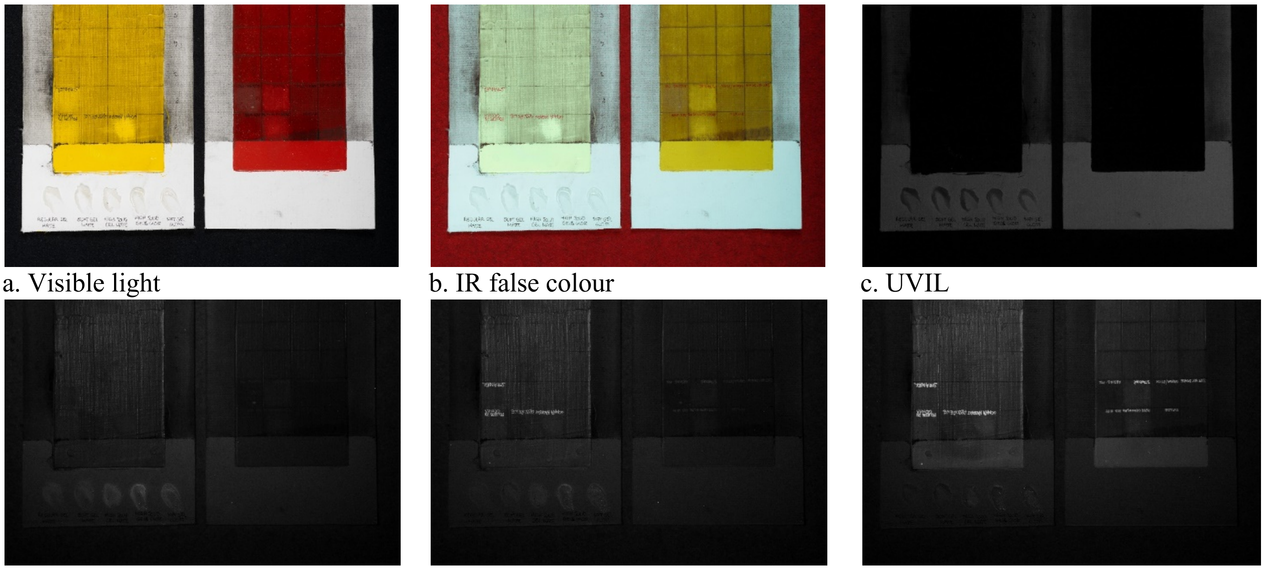
and GIL analyses bring some information on acrylic binder brushes on the bottom of the mock-up on the left (absence in UVIL). An interesting point is the luminescence produced by contemporary black ink in GIL and RIL mode and not in UVIL and BIL.

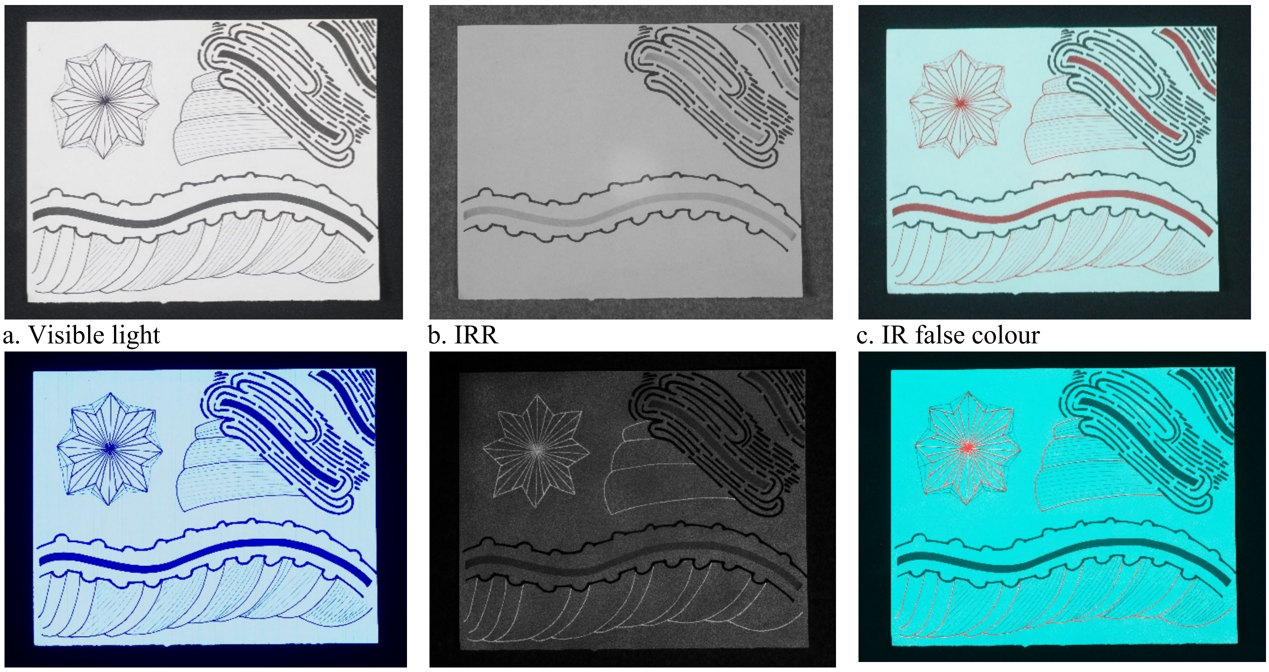


a. Visible light b. IR false colour c. UVIL

d. BIL e. GIL f. RIL

Fig. 11 – Two mock-ups with acrylic layer on primed canvas. e. and f. show the luminescence of ink.

Another example of luminescent contemporary ink is given in Figure N.7. Different inks from contemporary pens and markers are used to create a mock-up drawing. Multiband imaging campaign conducted on it, including VIL analysis, highlights different behaviours. Some inks aren't detectable by IR reflectography, but just one of them has a luminescence with VIL technique.



a. Visible light b. IRR c. IR false colour

d. UVF e. VIL f. VIL false colour

Fig. 12 – Mock-up drawing showing the behavior of different inks from pens and markers

Conclusions

VIL technique is confirmed to be a valid tool to detect some specific pigments in cultural heritage. Egyptian blue, blue and violet Han and cadmium-based pigments are the most studied materials that

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emit Infrared luminescence under UV or Visible light. Nevertheless, recent studies show that other pigments, dyes and binders can give luminescence with VIL technique and that could there be a synergy between pigments and binder. In particular, linseed oil seems to be the most luminescent binder among those presented in this paper. The observation of case studies and mock-ups shown in present paper confirm how a LED tuneable lights source could highlight different IR luminescence going from UV to red lights. In most cases specific identification, especially of modern and contemporary materials, is not possible. However further studies with compresence of VIL and other analytical techniques could help to discriminate some macro-categories of materials, pigments, dyes or binders. The creation of specific databases divided by art materials (like colored plastics, tissues and inks), historical period or artistic movement should be the begin of systematic studies on IR luminescence induced by monochromatic visible light.

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Combination of multiple analytical techniques for a holistic technical study of a 17th-century easel painting

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Abstract

Polychrome works of art that are entrusted to the care of scientists at the CCR "La Venaria Reale" undergo scientific investigation following a specific analytical protocol that allows for data acquisition within a stepwise methodological approach. The initial phase typically involves thorough documentation of the object's painted surface with photographic techniques and multiband imaging. The most frequently applied techniques among these include visible light photography (Vis-D, Vis-R, and Vis-T for diffused, raking, and transmitted light), infrared reflectography (IRR) along with false color processing (IRFC), ultraviolet-induced visible luminescence (UVL), and visible-induced infrared luminescence (VIL). These are often followed by analysis with X-ray digital radiography (XR). The resulting images are key to gathering preliminary information on the original materials and any later retouching.

Nevertheless, in most cases certain attributions cannot be made by these methods alone. Within the protocol described herein, photography and multiband imaging are typically integrated with other techniques that yield complementary, more in-depth data on the materials examined: firstly, non-invasive analysis using X-ray fluorescence (XRF) spectroscopy and fiber optics reflectance spectroscopy (FORS) is performed to provide an elemental and molecular characterization of the color palette; microscopic samples are then removed, mounted as cross sections, and investigated with micro-invasive techniques such as optical microscopy and scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDX) to gain insight into the artifact's paint stratigraphy in terms of morphology and composition of the individual layers.

This contribution will illustrate in detail the aforementioned analytical protocol as applied to the study of a 17th-century easel painting currently attributed to Italy's Lombardy-Venetia region. In light of the work's particularly complex provenance and conservation history, this project aimed to provide conclusive identification of the coloring materials and to discriminate the artist's original pigments from any later retouching. The wealth of data collected from this technical study enabled our research team to highlight a series of deliberate compositional changes, allowing us to trace some of the painting's most relevant vicissitudes that have occurred over time.

Keywords: multiband imaging, analytical techniques, materials characterization, easel painting.

Introduction

It is common knowledge that the scientific study of any artwork must follow a stepwise methodological approach, ensuring the investigation of different aspects of its production and conservation history. Nowadays, several analytical techniques are available, which are able to provide different types of information. The first step in the technical study of artifacts usually involves non-invasive techniques to preserve their physical integrity . Wherever necessary and - most importantly - possible, microscopic samples are removed from the artwork to address specific questions pertaining to the materials' composition (Saladino *et al.*, 2017). In all cases, the development of ad-hoc protocols tailored to the study of different artifact categories is of utmost importance (Fiorillo *et al.*, 2019; Toschi *et al.*, 2013; Zaffino *et al.* 2016). The Centro per la Conservazione ed il Restauro dei Beni

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Culturali (CCR) "La Venaria Reale" undertakes technical studies of various types of objects on a daily basis and, as a result, conservation scientists follow a specific workflow to gather information on the materials and techniques and to help address any extant conservation issues. When it comes to polychrome works of art, the adopted protocol typically involves a multiband imaging survey first, followed by non-invasive and, whenever possible, micro-invasive analysis, enabling a progressively deeper level of knowledge of the artwork. In this context, this article aims to emphasize the key role of a multi-step, systematic approach in the technical study of artifacts by elucidating the investigation workflow that paintings usually undergo within the CCR Scientific Laboratories. The case study selected for this purpose features a 17th-century easel painting from a private collection, portraying a young woman and attributed to the artistic production of Italy's Lombardy-Venetia region (Fig. 1). While providing an overview of the techniques employed, the manuscript will discuss the main results obtained by illustrating the variety of questions raised by art historians and conservators, along with the reasons that led to specific analytical choices.

Fig. 1 – Visible light photograph of the painting under study.

Materials and methods

A first assessment of the painting's materials distribution and conservation condition was accomplished through visible photography and multiband imaging. More accurate information on the pigments' composition is typically obtained with non-invasive pointwise techniques: in this study, the painting was analyzed using X-ray fluorescence (XRF) spectroscopy and fiber optics reflectance spectroscopy (FORS). Whenever possible, sampling provides a more in-depth understanding of the artwork's production technique and conservation history. In the present case, three multi-layered samples were removed from the painting and mounted as cross sections for analysis with optical microscopy (OM) and scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX), aiming to shed light on the paint stratigraphy and the artist's technique. Four scrapings of superficial varnish were also collected from areas of original paint and areas corresponding to two canvas bands that are believed to have been added at a later time. These materials were analyzed by means of transmission Fourier-transformed infrared (FTIR) spectroscopy. Further details on the instrumentation and experimental parameters used are provided below.

Imaging techniques

Visible photography and multiband imaging. All photographs were taken with a Nikon Z7 II Mirrorless Full Spectrum camera, modified to extend its spectral sensitivity in the 350-1000 nm range, equipped with a complementary metal oxide semiconductor (CMOS) silicon sensor as well as different filters, and providing a resolution of 8256 x 5504 pixels. For visible diffuse light photography (Vis-D) lighting was achieved by using two Elinchrom RX 1200 flashes, while for visible raking light photography (Vis-R) an 800-W Ianiro Varibeam Halogen lamp was placed to the left of the object with an angle of about 15° to the surface. Infrared light transillumination photography (IR-T) was performed by placing the flash behind the painting and using an IR 830 nm filter. Infrared reflectography (IRR) in the near-infrared range (NIR, 850-1000 nm) was obtained with the two aforementioned flashes and the IR 830 nm filter. In the short-wave infrared range (SWIR, 1200-1700 nm), images were acquired with a New Imaging Technologies WiDy SenS 640 camera equipped with an indium gallium arsenide (InGaAs) sensor, providing a resolution of 640 x 512

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pixels. IR false color images were obtained in the RGB color space of Adobe Photoshop by using two reflection images acquired in the Vis and NIR spectral ranges. In particular, the green (G) and red (R) components of the visible image are transferred into the blue (B) and green (G) channels, while the red (R) component is replaced with the NIR image. This methodology yields false color images of the NIR-R-G (RGB) type. For ultraviolet-induced visible fluorescence (UVF) lighting was achieved by using two 5-W Madatec LED UV lamps with emission peak at 365 nm. Two visible-induced infrared luminescence images were acquired using a continuous blue LED (BIL, peak at 450 nm) and a green LED (GIL, peak at 550 nm). For all the techniques above, image processing was carried out with Adobe Lightroom and Adobe Photoshop software.
Digital radiography was carried out using a tailor-made system equipped with a General Electric Eresco 42 MF4 X-ray source with a tungsten anode and a 0.8-mm beryllium window. A 2-mm aluminum slab is placed in front of the tube exit window to absorb the less energetic X-rays that are not useful for the radiographic investigation, thus limiting any beam hardening effects. The detector is a Hamamatsu C9750-20TCN X-ray Line Sensor Camera with a gadolinium scintillator coupled with a linear array of vertically arranged charge-coupled devices (CCD), resulting in a measurement area of 2560 pixels with 200-μm^2 size and 4096 gray levels (12 bit). Image acquisition, performed by means of HiPic proprietary software, is carried out by moving the detector horizontally along a motorized axis. In the present case, radiographs were collected using 50 kV voltage and 10 mA current. Images were corrected using white (X-ray source on, no object) and dark (X-ray source off) references. Image processing was conducted with a tailor-made software operating on the National Instruments' LabVIEW platform.

Non-invasive pointwise techniques
XRF. Analysis was performed using a Micro-EDXRF Bruker Artax 200 spectrometer equipped with a fine focus X-ray source including a molybdenum anode and a Si(Li) silicon drift detector (SDD) with an 8-µm beryllium window. Measurements were carried out using 30 kV voltage, 1300 µA current, 60 s acquisition time, 1.5 mm collimator, by fluxing helium gas onto the measurement area to improve the technique's detection limits (corresponding to Z=11, sodium).

FORS. Analysis was conducted using an Ocean Optics HR2000+ spectrophotometer and an Ocean Optics HL-2000-FHSA halogen lamp. The system includes two fiber optics, one single and one bifurcated, that are equipped with an Ocean Optics RPH-2 anodized aluminum fiber support. Spectra were acquired in reflectance mode with 2×45°/0° optical geometry. Spectra were interpreted by comparison with the available literature and spectral databases (Cavaleri *et al.*, 2017, https://spectradb.ifac.cnr.it/fors/)

Sampling and micro-invasive techniques
Cross section preparation. Cross sections were prepared by embedding each sample within a double layer of epoxy resin. After removal of the excess resin, the sample surface was finely polished using Struers abrasive cloths of progressively finer grits to expose the paint stratigraphy.

OM. Cross sections were observed and photographed under Vis and UV light using an Olympus BX51 minero-petrographic microscope equipped with an Olympus DP71 digital camera. Image acquisition and processing were performed by means of analySIS FIVE proprietary software.

SEM-EDX. Cross sections were analyzed with a Zeiss EVO60 scanning electron microscope equipped with a lanthanum hexaboride (LaB_6) cathode and an SDD, and coupled with a 40 mm^2 Oxford Ultim Max EDX microprobe for semi-quantitative elemental analysis. Samples were analyzed without any pretreatment in variable pressure mode, using an accelerating voltage of 20 kV and a pressure of 20 Pa.

FTIR. Analysis was performed with a Bruker Vertex 70 FTIR spectrometer coupled with a Bruker Hyperion 3000 IR microscope and equipped with a mercury cadmium telluride (MCT) detector. Scrapings were analyzed as a bulk in transmission mode through a 15x objective, upon compression in a diamond cell. Data were collected in the 4000-650 cm^{-1} spectral range, at a spectral resolution of 4 cm^{-1}, as the sum of 64 scans. Spectra were interpreted by comparison with the available literature and spectral databases.

Results and discussion

Visible light photography and multiband imaging allowed us to assess the painting's conservation condition, while guiding next steps in terms of scientific analysis. At first glance, all images show two canvas bands that are currently interpreted as later additions – one located in the upper part and the other on the left side of the painting. Paint cracking is observed across the whole surface, although it is more noticeable over the two added portions compared to the rest of the composition. This might point to the use of different techniques and materials in those areas. Vis-R images reveal an inhomogeneous surface likely due not only to the observed craquelure, but also to the accumulation and blistering of paint material through the layer induced by a previous treatment. The UVF image clearly shows the location and extent of retouching, displaying a different emission compared to the original materials. Retouched passages were identified on the woman's hair, flesh tones, and left part of her dress, where brushstrokes on the added band appear to extend to the central, original portion. A rather homogenous protective coating of organic nature is present onto the artwork's surface. Areas where the upper and left edges of the central portion were stitched to the two additional canvas bands are evident in the IR-T image. Moreover, it is possible to observe small paint losses now covered by inpainting. The IRR NIR image highlights the joints of the added bands, suggesting that a filling material might have been used to connect and then level off the edges. Furthermore, a blue retouching on the woman's dress is made evident by a different response to the wavelength used: while the original pigment partially reflects the IR radiation, the retouching paint absorbs it, thus appearing dark. In addition, the canvas weave shows through areas of the retouched paint losses. The IRR SWIR image yields additional information by revealing a poor conservation condition for the original paint. There is no evidence of the presence of underdrawings. IRFC, as well as the BIL and GIL techniques, delivered a map of the distribution of retouched areas thanks to a different response of the added materials to the wavelengths employed. Specifically, the luminescence induced by blue and green light highlighted the presence of retouching on the flesh tones, likely consisting of cadmium-based pigments (Thoury *et al*., 2011; Delaney *et al*., 2019). Lastly, digital radiography shed light on some of the painting's structural elements: the canvas is attached to the wooden frame with metallic nails (12 on each vertical side and 10 on each horizontal side), and surface planarity is ensured by expansion systems. Paint losses and the two added canvas bands are evident in these images.

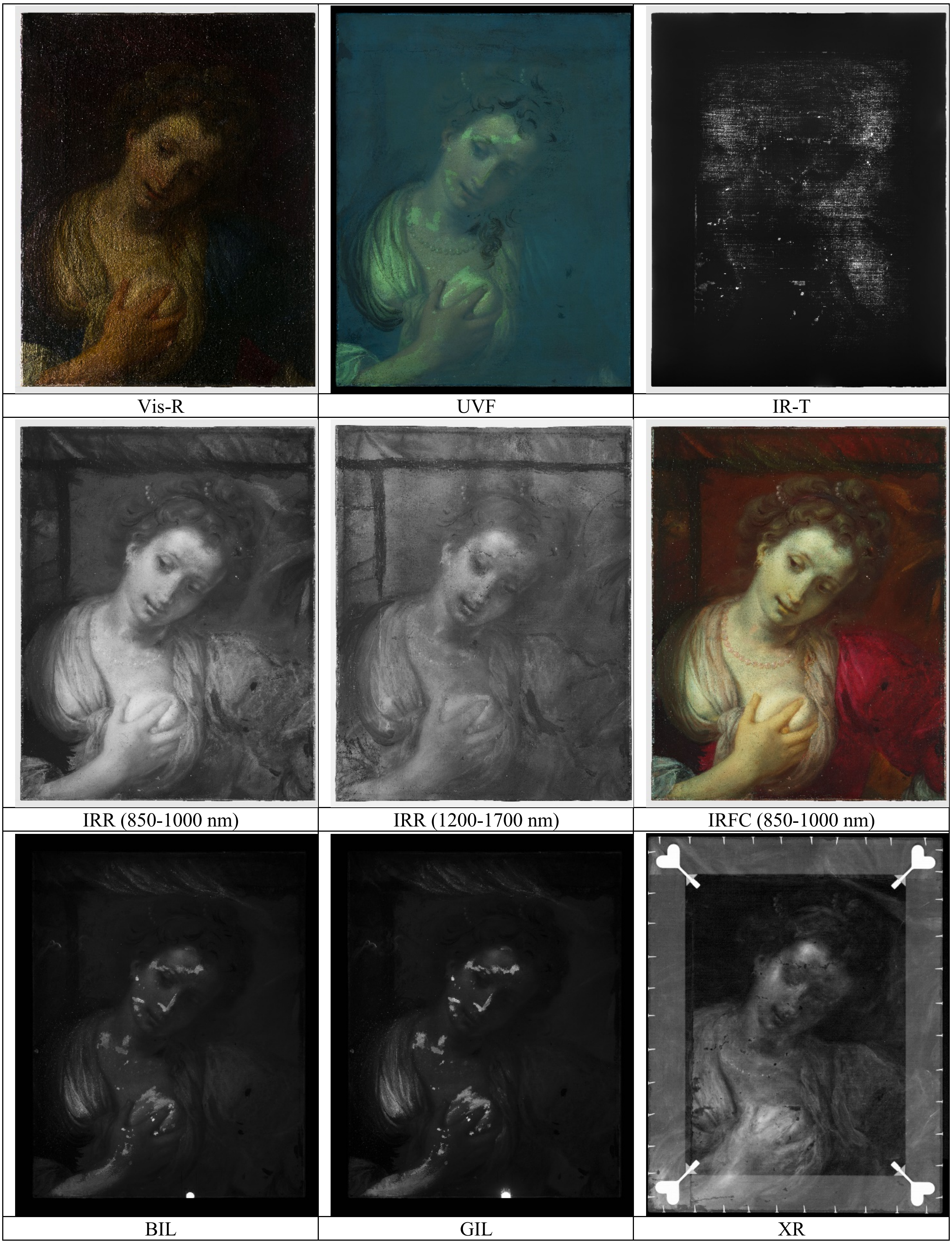

Fig. 2 – Multiband imaging documentation.

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Multiband imaging was key to guiding the selection of areas of interest for non-invasive point analysis. The combined use of XRF and FORS provided a preliminary overview of the color palette, whose composition is illustrated in the following paragraph. The woman's flesh tones are made with a mixture of lead white (basic lead carbonate, $(PbCO_3)_2 \cdot Pb(OH)_2$), vermilion (mercury sulfide, HgS), and iron-based earth pigments in different relative amounts to create different color shades. Her hair was obtained with lead white, bone and/or ivory black (carbon, hydroxyapatite, $Ca_5(OH)(PO_4)_3$, and calcium sulfate, $CaSO_4$), as well as iron-based earth and umber pigments, characterized by significant levels of manganese associated with the iron. The blue dress appears red in the IRFC images, suggesting the use of ultramarine blue (sodium silicate containing sulfur and aluminum, $Na_{8-10}Al_6Si_6O_{24}S_{2-4}$). This hypothesis is corroborated by the absence of elements related to any other blue pigments in the XRF spectra and, most importantly, by the detection of the pigment's typical FORS spectral features (Fig. 3), i.e. an absorption band at 600 nm and a rise in the observed reflectance in the red and infrared spectral regions. The dark red background is composed of iron-based earth pigments, lead white and/or minium (both associated with the presence of lead in the XRF spectra), vermilion, and possibly a red lake. The presence of the latter is hypothesized based on the shape of FORS spectra collected in this area.

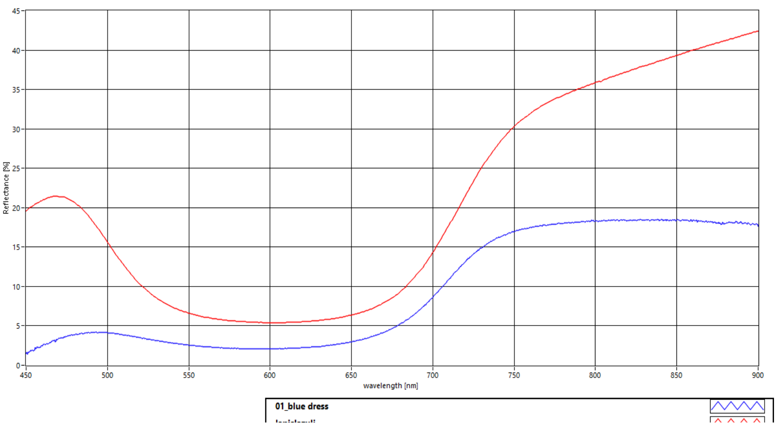

Fig. 3 – FORS spectrum of the blue dress compared to reference ultramarine blue.

In addition to the characterization of the original pigments and colorants, some of the materials applied within later interventions were also identified in this study. The detection of barium and zinc pointed to the presence of barium white (barium sulfate, $BaSO_4$) and zinc white (zinc oxide, ZnO), and/or lithopone (mixture of barium sulfate and zinc sulfide, ZnS) - all pigments that have been in use since the beginning of the 19th century (Eastaugh *et al.*, 2008). On the other hand, cadmium and selenium are related to the use of cadmium red (cadmium sulfoselenide, $CdSSe$), first commercialized in 1910 (Eastaugh *et al.*, 2008). The presence of this pigment was initially suggested by the blue- and green-induced infrared luminescence of certain retouching areas. In addition, XRF analysis of a blue retouch on the woman's dress revealed large quantities of iron, indicating the possible use of Prussian blue (ferric ferrocyanide, $Fe_4[Fe(CN)_6]_3$). Employed since the first decade of the 18th century onwards (Eastaugh *et al.*, 2008), the latter appears dark in the IRFC images.

A few materials-related questions were yet to be answered after non-invasive point analysis, which prompted a decision to remove a select number of microscopic samples for in-depth examination with micro-invasive techniques. Observation of a cross section from the painting's background in an original portion of the canvas (sample 07) under the optical microscope confirmed the use of a red lake, which was applied in three overlapping layers. This identification was based on the detection of a characteristic orange-pink UV-induced autofluorescence emission, as well as on the EDX identification of aluminum – a likely component of the inorganic substrate (i.e. alumina) on which the dye is precipitated during the lake manufacturing process (Fig. 4).

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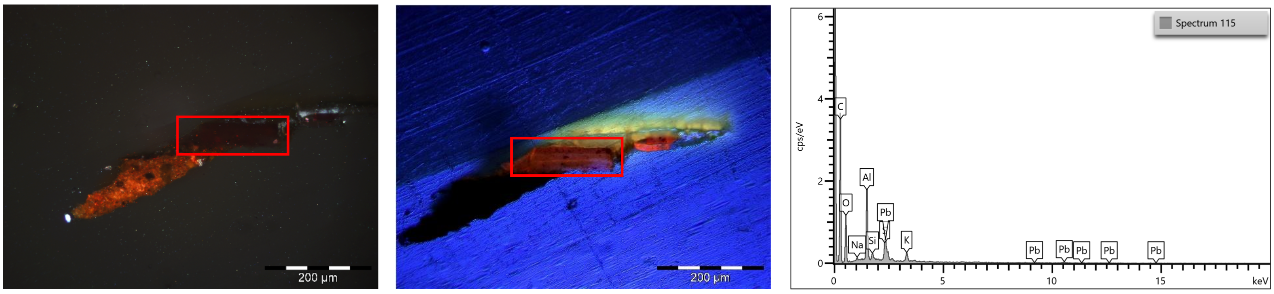

Fig. 4 – Cross section removed from the painting's background, showing the presence of red lake layers. OM Vis image (left), OM UV image (center), and EDX spectrum obtained from the area (right).

Moreover, a scraping of blue paint yielding a dark IRFC response was collected from an area of retouching on the figure's dress (sample 04): FTIR analysis confirmed the use of Prussian blue, characterized by a 2092 cm^{-1} absorption band due to the stretching of the carbon-nitrogen triple bond (Nawar and Maharani, 2023).

In light of the considerations made based on the combined use of non-invasive and micro-invasive techniques, a summary of the artist's color palette is provided in Table 1.

Table 1. Summary of the pigments and colorants detected in original and retouched areas of the painting under examination.

Color	**Materials identified**
Red	Iron-based earth pigments, vermilion, red lake, minium
Brown	Iron-based earth pigments, bone and/or ivory black
Blue	Ultramarine blue
White	Lead white
Flesh tones	Lead white, vermilion, iron-based earth pigments
Retouching	Barium white and zinc white (and/or lithopone), Prussian blue, cadmium red

As mentioned above, the UVF technique showed the presence of an organic material over the entire surface. FTIR analysis provided a characterization of this varnish layer, useful to a more comprehensive understanding of the materials and, more importantly, to support and guide treatment choices. In particular, all spectra obtained for four different samples (samples 01, 02, 03, 04), perfectly consistent with one another, enabled the identification of either a ketonic or a natural resin applied both on original areas and on the two added canvas bands. This confirms a homogeneous distribution of the protective layer across the whole surface, indicating that this material was most likely applied within a previous conservation treatment.

In addition to shedding light on the materials used, the examination of cross sections provided insight into the painting's conservation history. Three multi-layered samples were collected from the work's background to compare the original portion of the composition (sample 07) with areas from the two added canvas bands (samples 05, 06). In general, the stratigraphy of all these samples is characterized by a red preparation layer, composed of lead white and iron-based earth pigments, overpainted with both original brushstrokes and, in some cases, retouching as well. The multi-layered sample from the painting's original portion (sample 07) – discussed above – shows three red lake layers with a varnish coating on top (Fig. 4). The other two samples from the added bands (samples 05, 06) display a completely different sequence of paint layers, suggesting a different conservation history. These latter share the presence of two layers, one based on lead white probably associated with a blue organic pigment, the other obtained with a mixture of ultramarine blue and lead white. Although these two layers – which are absent in the original portion – appear in both samples from the top and left side of the painting, the overall paint stratigraphy looks different: in the upper band they are located immediately below the superficial iron-based red layer, while in the left side band they are followed by three brown layers (with iron-based earths, bone/ivory black, and lead white), an organic layer, and an uppermost dark red layer with an iron-based pigment and barium white. Although the preparation layers show strong similarities, it is clear that the observed added bands are different from the central, original portion of the composition.

Conclusions

This article illustrates the systematic, multi-step analytical protocol adopted at the CCR "La Venaria Reale", which combines imaging techniques, non-invasive pointwise techniques, as well as sampling and micro-invasive techniques to address specific questions and meet the unique requirements of each object. In the present study, the joint use of multiband imaging, XRF, FORS, OM, SEM/EDX, and FTIR delivered a comprehensive knowledge of the materials used by the artist, along with crucial insights into the painting's conservation history. For instance, in terms of pigment identification, the presence of ultramarine blue, initially hypothesized based on the red IRFC response of the figure's dress and the absence of any specific element in the XRF spectra that could indicate other blue pigments, was effectively confirmed by FORS analysis. Additionally, the use of a red lake, suggested by FORS spectra, was later confirmed by cross section examination. Another relevant example concerns the detection of some of the non-original materials: the use of Prussian blue in retouched areas of the dress was first deduced from the absorbance of IR radiation and high amounts of iron in the XRF spectra, and subsequently verified with FTIR analysis.

In conclusion, while each of the techniques used has potentialities and limitations, the integrated approach adopted in this study is able to provide comprehensive, complementary information, addressing most questions arising on the work's materials and techniques. In addition to revealing the color palette and paint stratigraphy in select areas of interest, the wealth of data collected in this study showed that the painting has undergone a complex history of transformations overtime, including the addition of two canvas bands added after the composition was initially conceived, the presence of later retouching, and the application of a non-original varnish.

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Evaluation of the effects of cleaning with essential oils on the colors of motion picture films

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Abstract

As conservation practices evolve, essential oils (EOs) are emerging as a sustainable alternative to traditional cleaning agents, offering effective and environmentally friendly solutions. This work aims to evaluate the impact of cleaning motion picture films with EOs on their color integrity. The research investigates the effects of four EOs on nitrate, acetate, and polyester-based films by analyzing changes in CIELAB color parameters before and after treatment. Advanced color measurements were conducted using a Konica Minolta CS-2000 Spectroradiometer with a 3 mm diameter measuring area, a 0.1° angle, and an 80 cm distance. A light-emitting diode (LED) light tablet with a color temperature of 5600 K, matched to daylight, was implemented as the illuminant and the white reference point for the L*a*b* values. Results revealed variations in color parameters depending on the type of EO used. While some EOs caused minimal changes, others led to shifts in the L* coordinate (luminance), indicating that the perceived brightness was primarily affected. The observed changes were minimal, with an average luminance difference (ΔL^*) of less than ±4 and an average color difference (ΔE_{76}) below 2. These values indicate that the changes in color and brightness were below the threshold of perceptibility for the average observer. The findings suggest that EOs may offer a promising alternative for film cleaning, although further investigation is required to assess their long-term effects.

Keywords: essential oils, motion picture films, film restoration, film cleaning, color analysis, CIELAB

Introduction

The preservation of motion picture films is a critical concern for archives, museums, and restoration laboratories worldwide. These materials face ongoing risks of degradation due to physical deterioration, chemical breakdown, and biological contamination, including fungal growth (Abrusci *et al.*, 2006; Bingley and Verran, 2014). Such damage can profoundly alter films' original characteristics, affecting color fidelity, image quality, and structural integrity, thereby diminishing their historical and cultural significance.

Film cleaning, regarded as one of the oldest conservation techniques (Enticknap, 2013), has traditionally relied on chemical solvents. While effective, these methods carry inherent risks to delicate emulsion and base layers, potentially exacerbating their degradation processes. Notably, many solvents previously employed have been phased out due to environmental concerns and potential health hazards, such as carcinogenicity (EPA, 2012). Isopropanol remains widely used for its relative safety and cost-effectiveness, although its dehydrating effects on film materials are well-documented (Bartels, 2017). Chlorinated hydrocarbons, favored for their non-flammability and efficacy in removing greasy contaminants, are still used in professional cleaning systems but under stringent environmental controls.

In response to these limitations, attention has turned toward alternative cleaning agents with lower environmental and material impact. Essential oils (henceforth referred to as EOs) have emerged as a promising candidate, especially due to their antimicrobial and antifungal properties (Hussaina *et al.*, 2013; Chouhan *et al*., 2017; Wińska *et al*., 2019; Broda, 2020). Derived from plants, EOs are complex mixtures of volatile and semi-volatile compounds with diverse chemical compositions, making them a versatile option for various conservation applications. However, their variability even in the same species (Fokou *et al*., 2020) and the prevalence of adulterated products necessitate rigorous quality control when sourcing EOs for conservation purposes.

Recent research has demonstrated the potential of EOs to inhibit microbial growth on paper documents (Borrego *et al*., 2016) and photographic materials (Ali, 2020). However, their impact on the color integrity of motion picture films remains underexplored. This study aims to bridge this knowledge gap by assessing the effects of EOs on the color properties of films, utilizing the internationally standardized CIELAB color measurement system introduced in 1976.

The CIELAB system, widely adopted in industries such as paper manufacturing and graphic arts, provides a robust framework for quantifying and communicating color (Sappi, 2013). Its application in conservation science (Garside and Richardson, 2022) has facilitated the evaluation of treatments on a range of cultural heritage materials, including mural paintings (Marchiafava *et al*., 2014), historical monuments (Zhang and Kruger, 2006; Goffredo and Munafò, 2015), and photographic media. The system's Delta E or ΔE metric, specifically the ΔE_{76} formula, offers a quantifiable measure of color difference (Johnston-Feller, 2001), with values above 5 generally recognized as perceivable to the average observer (Zhang, 2008; Mokrzycki and Tatol, 2011). This study leverages this analytical framework to evaluate the suitability of EOs as a cleaning agent for motion picture films, advancing both scientific understanding and practical conservation methodologies.

Materials and methods

Sample selection

The film samples analyzed in this study were obtained from the archives of the Deutsche Kinemathek in Berlin and the German Federal Archives (Bundesarchiv) in Hoppegarten, Germany. A total of 9 positive film strips (designated B1 to B9) were selected to represent a variety of film types commonly found in historical archival collections. The samples were in a stable conservation condition, exhibiting only minor surface soiling, slight mechanical damage, and no discernible signs of deterioration at the base or emulsion layer.

Prior to the cleaning process, the films underwent a comprehensive pre-treatment assessment to ensure that any changes observed post-treatment could be directly attributed to the cleaning process, rather than pre-existing damage or deterioration. Additionally, the samples were classified according to their material composition, including film base type, integrated color processes, and any applied color techniques. This classification was designed to facilitate a detailed analysis of the potential effects of the cleaning treatment across distinct material and color systems prevalent in archival film collections.

Essential oils selection

Four EOs were selected for testing, based on their documented applications in conservation literature and feedback obtained from a survey distributed among film archives and restoration laboratories through established professional networks. The chosen essential oils were:

1. Eucalyptus EO (*Eucalyptus globulus*)
2. Lavender EO (*Lavandula angustifolia*)
3. Rosemary EO (*Rosmarinus officinalis*)
4. Lemon EO (*Citrus limon*)

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The selection criteria prioritized oils with known antimicrobial and antifungal properties, as well as those with established safety profiles and widespread availability in conservation practices (Ali, 2020; Borrego *et al*., 2016) To ensure reliability and consistency, the quality and purity of each essential oil were verified prior to experimentation. Safety data sheets (SDS) were also reviewed to guarantee proper handling and application, minimizing risks to both the materials under study and the researchers involved in the process (Tisserand and Young, 2014).

Equipment and settings

Color changes were quantified using a Konica Minolta CS-2000 Spectroradiometer, operated with the Data Management Software CS-S10w Professional. Measurements were conducted with a 0.1° measuring angle on a 3 mm diameter measuring area at a distance of 80 cm from the sample. The luminance range (L_v) was set between 0.3 and 500,000 cd/m². The illuminant was a light-emitting diode (LED) light tablet, namely the DÖRR Ultra Slim LT-2020, with a color temperature of 5600 K, designed to match daylight. The CIELAB color system, with a 2° standard observer, served as the quantitative framework for the assessment of color differences.

The area inside the film perforations provided an additional white reference, with point measurements scaled to Lab 100, 0, 0. This approach established the L*a*b* values by referencing the light panel as the white point, thus avoiding the reliance on D50 or conventional "pre-press" reference standards. The illumination conditions were defined according to the correlated color temperature (CCT) in Kelvin.

The film samples were individually placed between two glass plates to maintain a uniform flatness during measurement. The room lighting was maintained at a consistent level throughout both measurement phases, prior to and following the cleaning of the film samples with undiluted EOs applied with a cotton swab. The second measurement was conducted eight days post-treatment to allow for any potential stabilization of the cleaning effects, such as evaporation of the volatile fraction of the EOs.

The total difference between the colors was calculated in accordance with the following formula (Mokrzycki and Tatol, 2011):

$$\Delta E^*_{76} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

In this context, ΔL*, Δa*, and Δb* (Table 1) represent the differences in the lightness and chromaticity coordinates. These correspond specifically to the differences in the red/green (Δa*) and yellow/blue (Δb*) axes of the two colors being compared (Sappi, 2013).

Table 5 - Color differences in the CIELAB system

ΔL* = difference in lightness/darkness value (+ = lighter - = darker)
Δa* = difference on red/green axis (+ = redder - = greener)
Δb* = difference on yellow/blue axis (+ = yellower - = bluer)
ΔE* = total colour difference value

Figure 1 presents the measurement points utilized, including the white reference derived from the LED light tablet employed to illuminate the film samples and the additional white reference measured from the area inside the perforations. Each point was measured 3 times to get an average value.

Fig. 13 - Color measurement points for film samples B1 (a) to B9 (i)

A statistical analysis of color changes (ΔE_{76}) was conducted, with the results plotted according to film type (black and white, applied color, or integrated color) and EO type. The data were processed using OriginPro 2018 software, with a box chart in the "Data Points Overlap" style for visualization purposes.

The study excluded the use of additional cleaning agents or solvents, thereby ensuring that the observed changes could be attributed solely to the EOs. Moreover, no accelerated aging processes were employed, thereby ensuring that the focus remained on the immediate and untreated film responses to the cleaning method.

Results

This section presents the results of the color analysis performed on film samples B1 through B9 before and after cleaning with the four different EOs. The table 2 provides a summary of the mean color differences (ΔE_{76}) derived from the measurements of the film samples. Further detailed data for each measured color, along with the calculated ΔL^*, Δa^*, Δb^*, and ΔE_{00} values, are available upon request.

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Table 6 - Color differences of film samples B1 - B9 after cleaning with EOs

Sample	Eucalyptus Oil	Lavender Oil	Rosemary Oil	Lemon Oil
	ΔE'76	ΔE'76	ΔE'76	ΔE'76
B1 - CN AGFA Tinted (Red)	4,31	6,47	8,32	3,53
B2 - CN ZEISS IKON Tin (Y)/Ton (B)	1,81	2,04	1,01	1,15
B3 - CN ZEISS IKON B&W	1,66	1,93	2,12	2,04
B4 - CA ORWO B&W	0,38	0,62	0,86	0,75
B5 - CA AGFA B&W	0,68	0,37	0,73	1,02
B6 - CA AGFA-GEVAERT Color	0,62	0,71	0,59	0,83
B7 - CA EASTMAN Color	1,17	1,05	2,01	1,02
B8 - PET EASTMAN Color	1,64	1,55	1,41	1,31
B9 - PET AGFA-GEVAERT Color	1,50	1,44	0,88	1,55

The graphs presented in Figures 2, 3, and 4 illustrate the statistical distribution of the total ΔE_{76} observed across groups of samples, categorized according to the type of color and EOs used in the cleaning treatment.

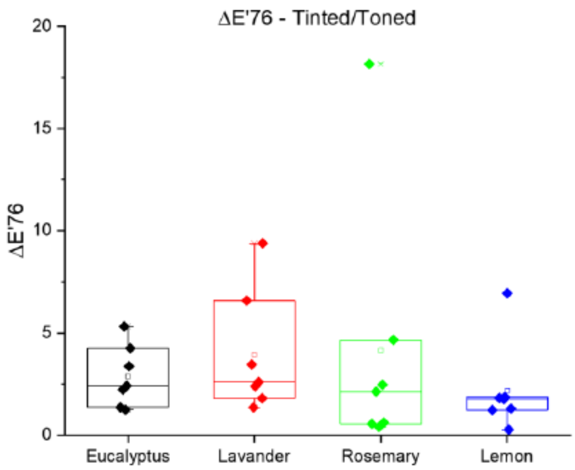

Fig. 14 - ΔE_{76} of film samples B1 and B2

As depicted in Figure 2, the samples that exhibited the most notable color differences on average subsequent to treatment with EOs were B1 and B2. Both samples have a cellulose nitrate base and were subjected to various applied color techniques, including tinting and toning.

The most notable changes were observed in the L* coordinate, particularly in sample B1 treated with rosemary EO, which exhibited a mean ΔL* value of 6.37. In contrast, the variations in the a* and b* coordinates were notably less pronounced, with the majority of calculated Δa* and Δb* values remaining below ±2 for sample B2. However, for sample B1, the Δa* exhibited values exceeding ±3 following the cleaning of black colors, with all EOs tested. The highest calculated value was 3.96, which was obtained using eucalyptus EO.

These findings indicate that the primary alteration occurred in the lightness of the samples, with minimal impact on their chromatic or qualitative characteristics. In other words, the chromaticity of the samples was not significantly affected (Lorusso, Natali, and Matteucci, 2007). With the exception of the results obtained for sample B1, cleaned with lavender and rosemary EOs, where the ΔE_{76} values exceeded 5, the mean values remained below this threshold. It is noteworthy that lemon EO demonstrated the most favorable performance, as the recorded color changes were consistently less than 4 on average for both samples.

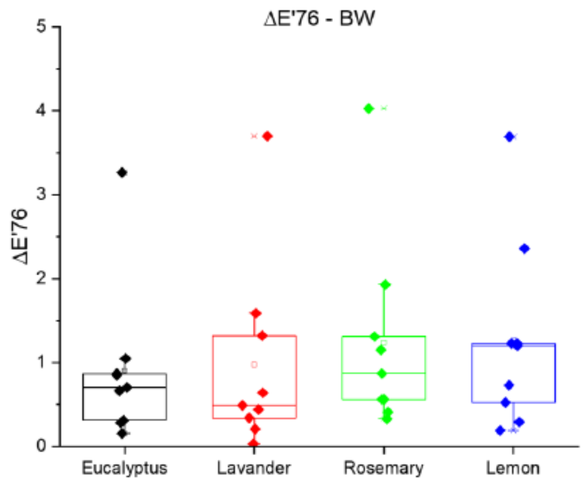

Fig. 15 - ΔE_{76} of film samples B3 - B5

The ΔE_{76} values calculated for the black-and-white film samples B3 to B5 (Fig. 3) exhibited an average value of less than 3 in all cases. Sample B3, which has a cellulose nitrate base, exhibited the highest degree of color change across all four EOs that were evaluated, reaching a ΔE_{76} mean value of 2.12 for rosemary EO. The most notable changes were observed once again in the L* coordinate, with a maximum calculated value of -3.98 for ΔL^* in the black areas of sample B3, cleaned with rosemary EO. The calculated values of Δa^* and Δb^* for black-and-white film samples remained consistently below ±1.

In this group, eucalyptus EO yielded the most favorable results, as evidenced by the average changes across all three coordinates and ΔE_{76}, which remained below 1, with only one exception observed for sample B3.

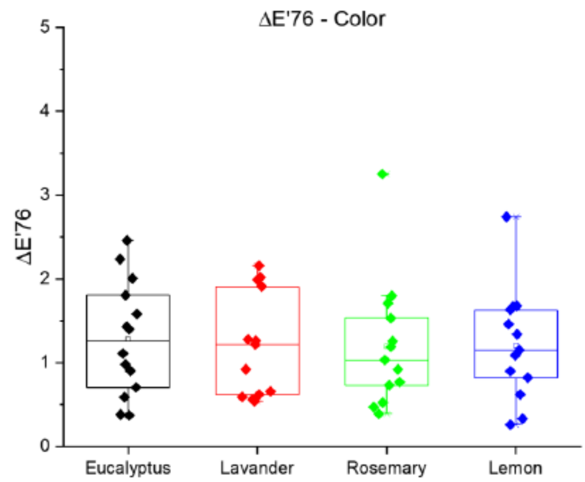

Fig. 16 - ΔE_{76} of film samples B6 - B9

The average ΔE_{76} values for the integrated color film samples, as depicted in Figure 4, were consistently below 2. Notable changes were again observed in the L* coordinate for samples B6 through B9. The highest calculated value of ΔL^* was 2.89 on a non-image/white area of sample B7 cleaned with rosemary EO, while the lowest value was -2.71 for grey on sample B9 cleaned with lemon EO. As in previous cases, the calculated values for Δa^* and Δb^* were, on average, less than

±1 across all samples, with the exception of Δb* for sample B7 cleaned with rosemary EO, which recorded a value of -1.45 for the color white.

It can be argued that the four types of EOs tested produced a relatively similar average effect on color changes induced by cleaning in all the samples of this group, with the exception of sample B6, which exhibited the least color change for all EOs used for cleaning. It is noteworthy that samples B8 and B9, which are polyester-based, showed negative ΔL* values in the non-image/white areas, unlike the other samples analyzed. This result suggests that these areas became darker after treatment, highlighting a distinct response of polyester supports to the cleaning process.

Conclusions

A review of the color analysis results reveals several noteworthy conclusions. The research indicated that the use of EOs for cleaning had a significant impact on the luminance parameter (ΔL*) across all film samples. The non-image areas and lighter colors exhibited increased brightness, as indicated by positive ΔL* values, with the exception of the polyester-based samples. Conversely, darker colors and areas with higher optical densities generally displayed negative ΔL* values, resulting in a darker appearance post-treatment. These findings suggest an overall modification in the perceived intensity of the colors (Lorusso, Natali, and Matteucci, 2007).

Changes in chromaticity, as indicated by the red/green (Δa*) and yellow/blue (Δb*) coordinates, were observed to be minimal, remaining within the ±1 range for all film samples subjected to analysis, with the exception of sample B1. This may be attributed to the red dye utilized for the tinting of this film and the potential interaction with the components of EOs.

The observed color changes remained within the acceptable thresholds for heritage conservation purposes, with none of the samples exceeding the ΔE_{76} average value of 5 (Goffredo and Munafò, 2015; Ali, 2020). However, certain film samples exhibited more substantial alterations. The samples B1 and B2 exhibited more pronounced changes in color, which can be attributed to the application of tinting (B1) and the combination of tinting and toning (B2). It is possible that the applied color techniques were more susceptible to chemical reactions with the components of the EOs. Nevertheless, no evidence of pigment loss, or color bleeding was observed during the cleaning process. It seems reasonable to suggest that these changes are attributable to the removal of substantial surface dirt, which was heavier on these older samples. This hypothesis is particularly relevant when considering the black-and-white samples. Among these samples, B3 exhibited the most pronounced color changes. As it was manufactured by the same company (ZEISS IKON) as sample B2, it is reasonable to conclude that it shares similar material properties (cellulose nitrate base) and historical context, which may result in comparable levels of accumulated surface dirt.

The black-and-white film samples exhibited the least color changes on average, likely due to the stability of metallic silver in their image composition compared to the dyes in chromogenic film emulsions. Interestingly, among the color samples, B6 showed the lowest ΔE_{76} average values, suggesting that its material structure, chemical composition and color process, identified as Gevacolor, contribute to greater stability.

These findings underscore the potential of EOs as a viable option for cleaning motion picture films while preserving their color integrity. It is recommended that future studies investigate the effects of EOs on a wider and more diverse array of applied and integrated color processes, as well as their interactions with polyester-based films. Furthermore, a comprehensive examination of the long-term effects of the cleaning treatment is essential for advancing research on restoration techniques in the field of film preservation.

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Wrappings and colors for eternity: scientific investigations on the votive animal mummies' manufacture

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Abstract

Votive animal mummies represent one of the largest categories of artifacts produced in Ancient Egypt. This specific type of mummy emerged in the New Kingdom (ca. 1550-1069 BCE) and increasingly gained popularity between the Third Intermediate Period and the Roman Period (ca. 1069 BCE-380 CE). Some animals were perceived to be the avatar of specific deities and deliberately killed in order to be sold as mummies to worshippers, who donated them to the corresponding gods in return of favors and protection. The external appearance of these votive offerings made them costly, thence increasing their value in the gods' eyes. As a result, these artefacts often show elaborate wrapping systems, made even more sophisticated by the interweaving with pale and dyed bandages. Often only mere scraps of colored bandages have survived, since they have mostly been degraded due to bleaching agents, used to obtain a better dyeing result, and the combination of different materials used in mordanting, especially iron compounds and tannins to reach a very dark color. To highlight the nature and spatial distribution of the dyes present on the bandages a multi-analytical protocol has been set up by combining multispectral imaging techniques (MSI) and fiber optic reflectance spectroscopy (FORS). The non-invasive proposed protocol allowed suitable identification of coloring matters used in the dyeing process and the reconstruction of the original appearance of the wrapping patterns. This paper aims to present the methodology and preliminary results of this study, as well as the challenges addressed, especially concerning the analysis of dyes present on this specific typology of artefacts.

Keywords: animal mummies, wrapping, textiles, dyes, MSI, FORS, digital humanities.

Introduction[1]

Animal mummies are one of the most intriguing aspects of ancient Egyptian religion. As early as the Predynastic Period (ca. 5300-3000 BC), Egyptians always believed that animals were the manifestation of the divine on earth, as suggested by the representation of real or imaginary animals on cultic and ritual objects as well as the sacrifice and burial of animals, in both human and independent graves (Hornung, 1967; Flores, 2003; Van Neer *et al.*, 2017). However, the oldest attestation of a cult addressed to an animal dates back to the Protodynastic Period (ca. 3000-2686 BC) (Simpson, 1957). Notwithstanding, the mummification of sacred animals surged in the New Kingdom (1550-1069 BCE ca.) and reached a peak between the Third Intermediate Period and the Roman Period (1069 BCE-380 CE ca.). Five categories of mummified animals have been attested so far (Ikram, 2019). Among them appears the so-called votive animal mummies, which increasingly gained popularity between the Third Intermediate and the Roman Periods. Although not sacred in themselves, some beasts (such as cats, dogs, hawks, ibises, crocodiles, snakes, fishes, shrews, and baboons) were perceived to be animal hypostasis of specific deities, thence deliberately killed and

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mummified to be sold as votive offerings to worshippers (Pubblico, 2023). Through the mummification process, these sacred avatars reached a semi-divine status, becoming an Osiris and the soul of the gods, they were associated with (Ray, 1979). Similar to human souls, the souls of the mummified animals might move through the earthly and spiritual worlds, acting as messengers through whom believers might easily address their concerns to the gods (Migahid, 1986). After being donated to the corresponding gods at their temples, millions of mummies were buried in different types of sacred necropoleis throughout Egypt. Hence, votive animal mummies represent one of the largest categories of artifacts produced in ancient Egypt, which could offer a rich source of information about a variety of aspects of ancient Egyptian civilization, including craft, economy and religious practices. Unfortunately, a great deal of data was lost through wild exploitation and trade in animal mummies, especially during 19th and early 20th centuries. Among the most popular antiquities brough home by Victorian travellers as a souvenir of their exotic voyages along the Nile valley, were mummified bodies or even parts of bodies. Animal mummies also rose in popularity as souvenirs, as they were cheap, easily portable and extremely fascinating in the eyes of visitors to the travellers' houses (Baber, 2016, 2019). During the mid-late 19th century, however, the interest in these curios was gradually decreasing. Consequently, animal mummies began to be used in papermaking, as wrappings supplied the high demand of rags used in newspaper production, and fertilizer industries, as the use of bone manure during the Victorian era was extremely common (Cooke, 2015, Baber, 2019, Elliot, 2023). The incessant exploitation of animal mummies for a variety of purposes as well as the unconventional and unrecorded removal of them from their burial places caused an unavoidable loss of data, especially concerning the mummies' date and provenience. This had in turn a great impact on their study with a long-lasting lack of interest in these artefacts in the field of Egyptology. Although this situation has changed over the last thirty years, with the number of projects devoted to animal mummies growing considerably, seldom have attempts been made to trace their contextual data (Ikram, 2019, 2023). This paper aims to present the methodology and preliminary results of a Marie Skłodowska-Curie project titled "A Study of Egyptian Animal Mummy Styles" (SEAMS), which goal is to investigate the mummies' bandage weaves to understand whether they could be markers of specific periods and places, through a totally non-invasive and cost-effective diagnostic methodology, that blends traditional research methods with new technologies. Thence, SEAMS seeks to address the current knowledge gap on contextual data of votive animal mummies and provides a thorough insight into their manufacturing process, including the dyes techniques of the bandages and the characterization of colorants used.

Votive animal mummies: challenges and project's objectives

The study of this specific typology of mummies is especially challenging since the vast majority are unprovenanced and it is difficulty to connect them with specific places of production and/or within a more refined time frame. Just a few Museums led more extensive radiocarbon dating on their animal mummy collections (Bruno, 2013; Wasef *et al.*, 2015; Richardin *et al.*, 2016; Porcier *et al.*, 2019; Pubblico and Oliva, 2019; Ikram *et al.*, 2024). This is mainly due to the high cost of the techniques, the curators reticence to samplings, and the struggle to collect suitable samples of the mummies under the wrappings without causing damages. As a result, only already unwrapped or very deteriorated mummies can be sampled, but often this poor state of preservation could cause contaminations of the sample, thus compromising the dating results reliability. On the other side, sampling only the bandages is not a very suitable alternative for dating these artifacts, as they may be older than the mummy itself, since the reuse of textiles (especially on mummies) is widely attested (Ikram *et al.,* 2024). Consequently, despite the massive numbers of animal mummies that have been found in archeological contexts, their dating is still difficult and unclear, and they are usually dating quite vaguely from the Late to the Roman Periods, which corresponds to the peak of the animal mummy phenomenon. Even more complicated is to determine their geographical provenience, as there are no scientific investigations which can, so far, provide to assign a geographic provenience to the mummies. Furthermore, unlike other forms of Egyptian material culture, animal mummies do not have an epigraphic apparatus that may help in reconstructing their story. The only aspect on which who produced them in a precise place and period left his "signature" are the wrapping patterns. In fact, while some features of the mummies remain unchanged over time, there was a great variety of wrapping styles (Bruno, 2013). Certainly, the mass production of these objects promoted a specific degree of craft specialization and changes at both a chronological and geographical level, especially in terms of wrapping techniques and styles. However, the wrapping waves of animal mummies have rarely been considered by Egyptologists both as a whole and as dating and geographic indicators. This situation partially changed in the last few years, when some scholars began to pay attention to the wrappings on animal mummies through visual examinations, yet only focusing on specific cemeteries, collections, and/or animal species (Letellier-Willemin, 2019; Atherton-Woolham *et al.*, 2019; Tarek *et al.*, 2019; McKnight, 2020; Ikram *et al.*, 2024). Taking its cue from these studies, SEAMS is widening the sample in terms of the species of animal mummy, the production sites and current location; and is systematically recording information on the weaving (yarns dimension, threats density, weave form), colouring (both dying and painting) and wrapping design of the bandages. This will ensure that data collection and analysis is carried out fairly. Three hundred animal mummies preserved in several museums around the world have been included in the research, chosen for their elaborate wrapping system and a related archive dataset. They consist of cats, dogs, hawks, ibises, crocodiles, snakes, fishes, and shrew mummies, mainly coming from necropoleis throughout Egypt. In this contribution, the preliminary results obtained on some of these specimens are presented by showing the outcomes of multispectral and spectroscopy analyses for the characterization of colorants in the wrappings.

Method

The experimental approach adopted in SEAMS project for studying and attempting to identify the colouring substances used in the dyeing process involved the combined use of multispectral imaging (MSI) and fibre-optic reflectance spectroscopy (FORS). Such non-destructive methodology aimed to avoid sampling nor micro-invasive techniques on votive animal mummies. Furthermore, a photogrammetric protocol, only mentioned here, was used in parallel to contextualise the colourimetric measurements and to obtain geometric precision and high-resolution detail in the resulting 3D models of the mummies, improving the legibility of the complex weaves. The combined approach here presented allow the study of nature and spatial distribution of the dyes extant on the bandages. The detection of dyed yarns of votive animal mummies wrapping is especially challenging since they are mostly degraded due to bleaching agents, used to obtain better dyeing result, and the combination of different materials used in mordanting, especially iron compounds and tannins to reach a very dark color. The usual fading of textiles and the layer of soiling often present further affect the recognition of coloring matters (Tamburini *et al.,* 2021).
The MSI method involves the acquisition of a set of images using a modified Canon 1200D camera and a set of filters. The modification consists of the removal of the inbuilt UV-IR blocking filter in order to exploit the full sensitivity of the sensor (c. 300–1000 nm). The lens used is a Canon EF 50mm f/1.8II and the camera works in fully manual mode. The investigated artifact is illuminated by an illumination source symmetrically positioned at approximately 45° with respect to the focal axis of the camera. A filter, or combination of filters, is placed in front of the camera lens in order to select the spectral range of interest. Thence, by using proper illumination sources, the reflectance and absorbance properties of the materials of the study object are recorded, including dyes such as in this

case. This technique allows to identify the spatial distribution and, in some cases, the chemical nature of the dyes present on the mummy bandages and facilitates comparisons between objects. The preliminary information obtained with MSI is then compared with FORS spectra (Ceccarelli *et al.*, 2022; Bacci *et al.*, 1992; Gulmini M. *et al.*, 2017; Tamburini D., Dyer J., 2019). This non-invasive technique shows specific spectral profile of materials that depends on the chemical characteristics of the sample. In this study, reflectance spectra were recorded with the Ocean Optics USB2000 Spectrometer with a sensor sensitivity in the 400-800 nm range. The instrument is optically coupled by means of fibre to a probe which was positioned in the most coherent areas with colours.
The combination of these methods is suitable for overcoming the limits of the single techniques and the challenges set by the nature of the wrappings, thereby allowing to collect reliable information on the compounds of colouring matters.

Results

As preliminary outcomes, the results of MSI and FORS analyses on the ibis mummy 4918-2 preserved at the Carnegie Museum of Natural History in Pittsburgh are shown (Fig1). The bundle is wrapped with horizontal and vertical bandages interlaced to create square lozenges, secured on all sides by further pieces of fabric. The decorative module is made even more sophisticated by the combination of apparently undyed and dark brown bands. In fact, the pieces of fabric placed on the sides of the bundle have secured the original colour of the bandages placed underneath them from the natural discoloration of fibres which instead affected the colour readability of the exposed area of the strips (Fig.1b).

(a) (b)

Fig. 1 – Ibis mummy 4918-2, Carnegie Museum of Natural History (Pittsburgh): (a) general image; (b) detail where the original colour of the bandages are visible. (ph. Credits: courtesy of Carnegie Museum of Natural History (Pittsburgh).

The original hues of the decorative module have been unravelled through the proposed workflow: the slightly pinkish luminesce of the bandages in the UVL image (Fig.2a-b) could suggest organic red colorant, possibly madder, which in lighter reds or dark pinks nuance commonly emit pink luminescence under UV irradiation. This is further confirmed by FORS spectra (Fig.2c), which shows an intense emission band close to ca. 600 nm, a distinctive feature for madder (Tamburini *et al.*, 2019).

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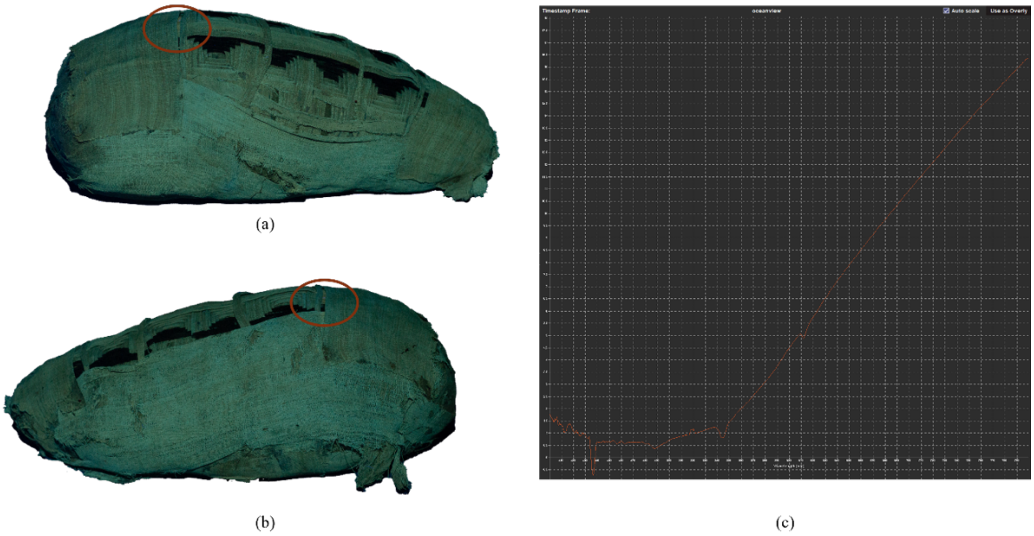

Fig. 2 – Analyses on the reddish bandages (red circles) of ibis mummy 4918-2, Carnegie Museum of Natural History (Pittsburgh):
(a,b) UVL images with a focus on the reddish colorants, confirmed by (c) FORS spectrum.

Concerning dark bandages, the evident absorbing behavior under UV illumination provides a very dark color in the UVL image (Fig.3a,b), being indicative of the use of tannins. They result in a variety from light to dark brown hues, depending on the combination with iron compounds (Tamburini *et al.*, 2021). By observing the FORS spectrum (Fig.3c), inflection occurring close to but greater than ca. 730 nm validates the MSI observation.

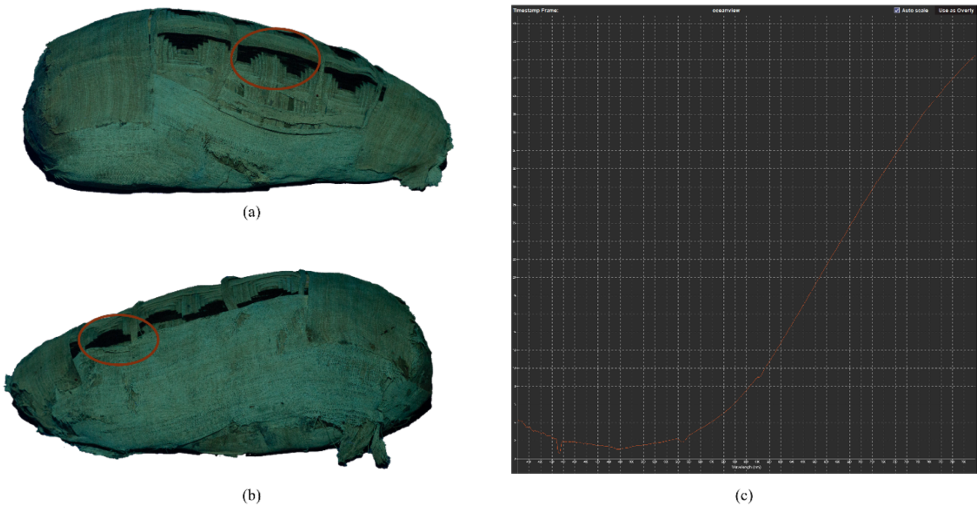

Fig. 3 – Analyses on the dark bandages (red circles) of ibis mummy 4918-2, Carnegie Museum of Natural History (Pittsburgh): (a,b) UVL images and (c) FORS spectrum.

Given that the measurements collected on other areas of the mummy showed enough characteristic features in the FORS spectra, either absence of coloring matter or presence of an unidentified yellow dye has been suggested. In these cases, sampling coupled with minimum invasive investigation might offer definitive conclusions. Notwithstanding, the proposed protocol provides enough data to proceed with the comparative investigation of the colorants present on the mummies under study that, coupled with the comparative analysis of their patterns morphology, may offer information about local beliefs linked to stylistic designs, wrapping techniques or raw materials choices. At El Deir in the Kharga oasis, for example, both the human and dog mummies were wrapped with reddish bandages (Dunand *et al.*, 2017). This constitutes a renown local practice and a precise economic choice which allows the definition of a regional style.

Final remarks and conclusions

Votive animal mummies offer a rich source of information about a variety of aspects of ancient Egyptian civilization, especially craft, raw materials, religious practices and economy. Unfortunately, the lack of contextual data has had a significant impact on the interest in these artifacts, which have long been neglected by scholars and regarded as mere curiosities and an odd expression of later Egyptian religion. The SEAMS project has as main objective to fill the gap in current knowledge on the contextual data of votive animal mummies through the analyses of stylistic variations of recurring wrapping weaves. This study not only gathers new data from which to understand whether they were traceable to specific production centres, thus further contributing towards contextualizing the geographic provenience and chronology of the specimens under study, but also offers a unique insight into the animal mummy craft, including scientific information on the variety of colourants used to produce the elaborate wrapping systems. The results of MSI and FORS analyses showed coherent data with the general knowledge on the dying textile process. Indeed, the red colours identified as madder (Rubia spp.) is in line with the popularity of the colourant as it was probably the most important dye of plant origin in Pharaonic Egypt.

The virtual stylistic restoration is subsequently undertaken to fill any volumetric and chromatic gaps of patterns in the digital replica by using both tangible evidence and objective data obtained through photogrammetry, MSI and FORS. This produces a digital edition of the mummies, which corresponds as much as possible to their original appearance. They will be particularly important for the last research phase, which involves textile and experimental archaeology protocols to reproduce exact replicas of the recurring wrapping patters using the digitally restored 3D entities as their main references, which will further an understanding of the wrapping *chaîne opératoire*.

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Color and Design - Color and Culture

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“Who is afraid to sit on a rainbow bench?” Contemporary color solutions for benches and seating units in public spaces - selected issues

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Abstract

The article aims to analyze and categorize selected color solutions used today for elements intended for sitting in public spaces. The research results are discussed and presented in three categories, each concerning a different way of applying color to seats according to their primary function in the space. The first group consists of typical city and park benches. Since their superior features are functionality and practicality, in most cases, their dominant colors are connected with their construction material—brown for wood, grey for stone or concrete, or black or green for metal. The second group includes individual seats designed as unique accents in public spaces. These seats are often created as temporary installations, as a result of competitions or artistic activities, and their expressive colors and/or unconventional forms often evoke extreme emotions among observers. The last discussed group forms seats designed as an important and sometimes even essential element of a given public space. Their color becomes the leitmotif of visual identification and gives the place character. Only one color is often chosen for those seats to increase the monochromatic effect in the space.

Keywords: color, bench, urban furniture, public space, color design

Introduction

Benches are a specific element of urban furniture that combines the practical-ergonomic aspect with the visual-aesthetic one. It is not only a place for individual rest and relaxation but also for integration and establishing social contacts and conversations. There are many styles and forms of seating in public spaces - traditional and contemporary benches, minimalist and decorative, long and short, with and without backrests...

Street benches belong to a broad category of urban furniture that appeared with the development of 19th-century urban agglomerations, including street lamps, mailboxes, advertising columns, posts and fences, waste bins, public toilets, and others. The term "urban furniture" was coined in the 1960s with the development of multi-aspect design for public spaces (Grabiec et al., 2022). As a landscape element, urban furniture should be consistent in style and appearance, spatial structure and meaning, and harmoniously blend with the surrounding environment, which includes architecture, communication routes, and green areas (Prvanov, 2017). Mass-produced city benches became popularized during the Industrial Revolution in Europe, but they had their predecessors already in antiquity. Stone seats were an essential part of Greek and Roman amphitheaters (Uslu, Bölükbaşı 2019). Turf benches were installed in medieval gardens. These were raised beds covered with grass, the structure of which was made of bricks, boards, or willow branches. They could be free-standing or attached to a wall. This type of bench changed its color according to the changing colors of the whole garden (Harvey, 1990). During the Middle Ages and the Renaissance, city benches could be found in public squares. In thirteenth-century Florence, monumental stone benches formed the furnishings of the Piazza della Signoria, where important city celebrations were held. The form and material directly referred to architecture and sometimes were an element of it - the benches were made of stone, the same as the building's facade (Elet, 2024).

Materials and methods

The issue of benches as elements of "urban furniture" has been the subject of extensive research and a rich literature (see, e.g., Gamito et al., 2014; Wang et al., 2015; Farrokhirad, 2018; Bolkaner, 2019; Grabiec et al., 2022). Still, references that analyze them separately and categorize data about their color choices are scarce. That provoked authors to research the topic and set the article's goal to analyze and categorize selected color solutions used today for all elements intended for sitting in public spaces.

In the spatial context, the authors focused on the Western world in a broad sense, including Europe—with particular emphasis on Poland, the author's country of origin—and both Americas, not ignoring other regions of the world, too.

The analysis of the use of color for benches was primarily based on a review of relevant literature, a detailed survey of the websites covering projects of different seats from around the world, and the offer of leading bench manufacturers in the European market. The authors also based their research results on their expertise and analyses of benches they photographed during their trips to Austria, France, Germany, Great Britain, Greece, Italy, Portugal, and Sweden (Fig.1).

For a more comprehensive presentation, the authors grouped the research results into types of solutions used today in selecting the colors for the benches.

Fig. 1 Selected examples of different colors of benches collected by the authors during their travels - a collage of photographs by Justyna Tarajko-Kowalska, 2024

Results

The research results are discussed and presented in three categories, each concerning a different way of applying color to seats according to their primary function in the space.

The first group consists of the typical city and park benches. The second group includes individual seats, designed as unique accents in public spaces and often created as temporary installations as a result of competitions or artistic activities. The last discussed group presents seats designed as an important and sometimes even essential element of a given public space.

Typical city and park benches

The Industrial Revolution of the 19th century brought mass-produced street furniture made of cast iron, most often painted black or green, into common use. The leading producers of cast iron benches were Great Britain, France, and Italy, each of which developed a slightly different style (Soffritti et al., 2020).

A classic example of a French bench from the mid-19th century is the "Paris bench" by Gabriel Davioud in 1850. It was intended as a resting place for pedestrians crossing the streets, widened as part of the reconstruction of Paris carried out by Georges-Eugène Haussmann in 1853-1870. The first

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Parisian benches appeared on the Grands Boulevards. They consisted of a decorative, cast-iron structure with the coat of arms of Paris, on which a wooden seat was placed. The cast iron elements were dark gray, and the beams were painted dark green. Gabriel Davioud also designed an entirely wooden gondola-shaped bench (fr. *le banc gondole*), allowing for a more comfortable position. It was used primarily in city parks, and usually was painted dark green (Rybczyński, 2024).

In the 19th century, public parks appeared in European cities, which required providing visitors with the necessary infrastructure, including, in particular, places to sit. At the same time, greenery was considered an antidote to civilizational pollution. As Pastoureau wrote: "Delicate or fresh green for the plants, dark or grayish green for the objects; in the public square, the palette of greens was extremely vast" (Pastoureau, 2014).

The Fermob chair, designed in 1923 for the Jardin du Luxembourg, was also an important example of Parisian park furniture. Its primary color was greyish green called Cactus. At the end of the 19th century, cast iron furniture was also popularized in the United States. An example of a city where benches have become a symbol of the local community is St. Petersburg, FL. The first city benches appeared in 1908, and in 1916, the city council decided on their specific shape and color. A green called Hunter Green was chosen and was used consistently until the 1960s. Green benches from St. Petersburg could be seen on popular postcards. More than 7,000 benches of that type were manufactured and placed in the city (Mudano, 2013).

Nowadays, thousands of benches are in cities, and regardless of their utility functions, they are also an element of the place's visual identity. The colors of city benches result from the type of materials used, technology, and style, as well as the legal regulations adopted in a given area, local traditions, and color preferences. Since the life of a city bench is long, there are benches with very different styles next to each other, and then the color is an organizing element.

Based on the analysis of the offers of leading European manufacturers of street furniture (AMV, Area, Eastgate, Mmcite, Fulco, Zano, KØBENhagen OUTstanding, Puczyński et al.), it can be noticed that the colors of city furniture proposed today are closely related to the nature and coloring possibilities of the materials used, which are: steel, aluminum, cast iron, concrete, wood, granite, HPL laminates, polyurethane, etc. In the case of wood, the surface is protected or colored with a transparent coating so that the natural structure of the material is visible, and the color is associated with a specific type of wood. The color palette of powder-coated metal benches, recorded in the RAL notation, is based primarily on neutral colors such as RAL 9005, 9007, 9010, and 9011. Of course, on request, it is possible to choose any color from the RAL, RAL Design, NCS, and other palettes.

Benches with cast iron elements sometimes refer to tradition in their colors through the use of greens, e.g., RAL 6005, 6011, 6018, 6021, or RAL Design 190 30 15 (Carriage Green). In modern street benches, a metal structure is often combined with a wooden seat, as in the "Warsaw bench" designed in 2019, consisting of a graphite-colored steel frame and an oak or beech wood gondola. The bench, created by Jerzy Porębski and Grzegorz Niwiński, is an element of the visual identity system of the Polish city of Warsaw (Porębski, 2024).

Benches made of stone, most often granite, characterized by shades of grey, usually polished, are used in historic city centers, e.g., Poznań or Kraków (Poland). Due to its widespread availability and resistance to weather factors, designers also willingly use concrete. In addition, various natural aggregates added to concrete, including grit, Portland cement, and Riverstone, allow for the modification of the surface and color. Concrete benches often have a wooden board finish on the seat or backrest, which improves comfort and introduces additional color.

City furniture made of plastic has an entirely different color palette, usually intense, saturated colors that contrast with architecture and greenery. Benches of this type appear in modern developments or around museums and contemporary art galleries, an example of which are the polyethylene Enzi benches, designed initially for the MuseumsQuartier in Vienna, Austria (Sommariva, 2010).

Designing urban furniture made of recycled materials is a contemporary tendency, resulting from environmental concerns. Dyeing recycled plastics is difficult due to the diverse colors of waste from

which the granulate is obtained. Particular difficulty applies to light colors and those with high saturation, which require precise waste sorting (Lifocolor, 2024). Designers from the Dutch studio The Zero Waste Lab created recycled urban furniture as part of a campaign called Print Your City. From collected PET bottles, benches, flower pots, and bicycle racks were created in the 3D printing process for the Greek city of Thessaloniki. Their color palette includes grayish shades of red, yellow, and blue. The material was colored in the mass with special, ecological dyes (Zys, 2019).
In the approach to the colors of city benches, one can notice a clear difference between the restrictions introduced by the local administration, aimed at unifying and narrowing the color palette of city benches, and the needs of residents, who often choose colors with much greater saturation. For example, benches painted an intense blue bench in Tomaszów Mazowiecki (Poland) gained great sympathy from local community (Tomaszów Mazowiecki Nasze Miasto, 2021).

Individual seats - unique accents in public spaces

The next group of seats are individually designed benches, constituting accents in public space, as well as temporary installations, created as a result of competitions or artistic activities, with expressive, often highly saturated colors, and unconventional form, sometimes evoking extreme and even negative emotions among observers. A large color diversity characterizes this group because they are selected individually for each seat, often produced in only one copy.
Based on the analyses, three characteristic subtypes were identified in this category: ideological benches and benches "with a message," "artistic" benches - for competitions and accompanying cultural events, and oversized benches-monuments.

Ideological benches and benches "with a message"

This category includes benches that often have standard shape but are painted in colors with a specific symbolic or cultural reference. In this case, the color of the seat often becomes more important than the seat itself, and its function goes far beyond simple utility.
The largest group here are seats painted in rainbow colors, which refer to the colors of the LGBTQ+ community flag and symbolize tolerance and equality.
An example here is a series of eight blue benches with rainbow seats located in different places in the Finnish city of Espoo. The popular Tapiola bench designed by Aarne Ervi, which has been a familiar part of the Espoo cityscape for many years, was used to implement the Pride bench project. The first rainbow-colored bench was introduced in 2021 in honor of Pride Week (Espoo Esbo, 2021). However, local communities do not always receive rainbow benches positively. In Poland, ruled until 2023 by a right-wing political party, the LGBTQ+ community was discriminated, and its symbols present in public spaces often became the target of acts of vandalism. It was no different with benches painted in rainbow colors, although in several cases, the initiators of giving the seats rainbow colors did not connect this fact with any ideology and just wanted to diversify the colors of city benches. An example is the design of 12 places for rest and recreation in Leszno (2019), whose common compositional elements were rainbow seats and tables. The project was met with numerous negative opinions and even declarations of refusal to sit on rainbow benches due to the association of their colors with the LGBTQ+ community (Leszno24.pl, 2019). The location of the rainbow benches in Kielce (2021) was also controversial, and the benches were systematically devastated. The scale of vandalism was so large that the city authorities considered changing the colors of the benches or moving them (Węglarczyk, 2021). Ultimately, the benches remained, but from time to time, they were still destroyed, although to a lesser extent than immediately after installation (Walczak, 2022).
The next group consists of benches "with a message," which serves as a kind of sign in space, a symbol intended to draw attention to a specific phenomenon or problem. Their color can be immediately recognized and associated, or its meaning can only be understood thanks to information campaigns. Seats of such type are created as individual happenings or as large-scale projects on the initiative of various groups or foundations.

An illustration of the first type may be the action of painting two benches in Gdańsk (Poland) - one in the colors of the rainbow, the other in the colors of the Ukrainian flag - yellow and blue. The event aimed to show the city's openness to diversity, emphasizing opposition to the war in Ukraine and broadly understood discrimination of various social groups (Kozłowska, 2022).

The second type can be represented by the Australian Red Rose Foundation's campaign, "Red Bench: Domestic Violence - Changing the Ending," which included the installation of over 500 red benches in public locations. Their presence was aimed at raising awareness of domestic violence and providing an opportunity for this important issue to remain visible (Red Bench Project, 2023).

An interesting, although ultimately unsuccessful, project was the so-called "patriotic bench." The benches, installed in 2022 in 16 Polish cities, with a shape resembling the country's borders and painted in its national colors - white and red, were supposed to evoke theoretically positive associations. But ultimately, the benches caused a lot of controversy, among others, due to their not completely well-thought-out appearance, high price, and low quality of workmanship (Głaz, 2022). The impermanence of the benches and negative opinions finally resulted in the decision to dismantle them (Gdak, 2023).

However, benches with red seats and white backrests decorated with a multicolored floral motif inspired by Polish folklore were erected in the summer of 2024 in Aurea, Brazil. This small town of 3.5 thousand inhabitants, founded in 1906, is inhabited 90% by descendants of immigrants from Poland, and since 2022, Polish has been the official language in the commune. The benches, which express the residents' Polish patriotism, were designed by Adriane Barp and her daughter Lara (Kowalczyk, 2024).

"Artistic" benches - for competitions and accompanying cultural events

This group includes benches and seats designed as part of architectural and design competitions. They are usually made in a single copy and presented in public spaces during a given artistic event. Similar to the previous group, their colors are highly diversified and often bright.

Particularly noteworthy in this group is the cyclical competition titled City Benches, which has been organized annually since 2019 as part of the London Festival of Architecture (London, UK) (Crock, 2021; City Benches, 2021). The seats, with an unusual form, often significantly different from the traditional one, and an equally unconventional color scheme, are created as an artistic manifesto of young architects and designers. The benches selected for implementation are installed in chosen places in London and are a showcase and advertisement for their designers during the festival.

This category also includes collections of seats located in particular places, whose characteristic feature is an artistic effect. The colors of the benches in this group are usually designed individually by artists, and their creation is related to a specific program, e.g., space revitalization or a promotional campaign.

An example here would be The Art Benches of Palm Springs, CA project, which started as a collaboration between the Main Street Merchants of downtown of Palm Springs and the Palm Springs Public Arts Commission, under which 70 dark-brown cement benches in downtown Palm Springs, intended by the city authorities for replacement were transformed into works of art (2019). A different artist painted each seat in various patterns and colors, and a map with detailed locations was also prepared. This program managed to save substantial expenses while promoting the work of the local artists in Palm Springs. Today, the multi-colored benches are one of the city's most important tourist attractions (Condon, 2021).

A similar action was "Take a Seat Vienna," initiated by the non-profit organization The Vienna Arts Society (VAS). It ended in November 2023 and involved 40 individual bench painting projects by local artists. Wooden benches decorated with a wide range of patterns and colors decorated the main streets of the city of Vienna, VI, and were then auctioned, the proceeds of which were allocated to the operation of VAS (VAS, 2023).

An interesting initiative is the "Zaczytane Ławki" (literally “Benches full of reading”) project, which

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aims to promote reading in Poland since 2018. It is a series of original, colorful benches in the shape of open books, the pattern of which is painted as the result of joint work of the ambassador and the artist or the artist's independent work. Benches can create the temporary exhibitions consisting of eight benches or function as individual, permanent element of the space. The graphic design of the bench is selected from the catalog or created according to the needs. Currently (2024), there are about 60 of those benches (Zaczytane Ławki, 2023).
Another project presented in this group is a series of seats by Danish artist Jeppe Hein, created since 2006 and named Modified Social Benches (MSB). The design of the benches, although borrowing their basic form from the ubiquitous park or garden benches, "is altered to various degrees to make the act of sitting a conscious physical process." The seats, made of powder-coated galvanized steel, later aluminum, are always painted in one color. In the subsequent stages of the project, different colors of the benches appeared - white, red, or blue. They are displayed temporarily as part of exhibitions or as permanent installations in various locations worldwide (Jeppe Hein, 2023).

Oversized benches-monuments

The next group's characteristic feature is the scale of the seats. Although the benches' form remains typical, their large scale not only distinguishes them from the surroundings and attracts the observer's attention but also deprives them of their usual ergonomics, making using them a challenge and creating new experiences. Their colors are also important.
The most recognized project using large-scale benches is The Big Bench Community Project. The first Big Bench - "BIG RED BENCH #1" - was constructed in 2010 by Chris Bangle on the Borgata grounds in Clavesana (Piedmont, IT), where he resides and has his design firm, as an installation looking out onto the panorama and is accessible to guests. The project encourages the installation of colorful benches in publicly accessible spots with beautiful views. Since each bench is supposed to be unique, the project's creators decided that in addition to single-color benches, they can also be two-colored, in which a separate color is selected from the RAL palette for the iron structure and another for the wooden seat. No patterns, rainbow colors, team colors, or natural materials are allowed. In 2024, there are 390 existing benches and 63 benches under construction, most of them in Italy. Still, there are also some, among others, in Spain, Germany, Poland, Slovenia, Romania, and the UK (Moncada, 2016; The Big Bench Community Project, 2024).
A specific phenomenon in the category of oversized seats is that most of them are colored red, which attracts the observer's attention even more and contrasts with the surrounding landscape. An example is a giant red chair bolted to a rock on a remote mossy hillside in Iceland. There is no information regarding its origins or the purpose of its presence in this desolate but beautiful place, located on the popular tourist trail Iceland's Route 1 (Red Chair, 2019).
Red chairs can also be seen in Canada, where several independent projects using the form of so-called Adirondack chair, invented by Thomas Lee between 1900 and 1903 in Westport, NY, and later popularized in tuberculosis sanatoriums (Judge Silber, 2021). In 2011, the Parks Canada Red Chairs project was launched in Gros Morne National Park, which involves installing pairs of red Adirondack chairs in lesser-known but stunning locations, inviting visitors to enjoy and share on social media with #ShareTheChair. Today (2024), over 400 iconic red chairs are in over 100 locations administered by Parks Canada (Parks Canada Red Chairs, 2023). The Big Red Adirondack chairs also appear as temporary tourist attractions in various provinces in Canada, e.g., Meaford, ON (The Big Red Chair Tour, 2017), Steinbach, MB (2023).
In 2017, as part of the 110th anniversary celebration, Sobeys Inc., the second largest supermarket network in Canada, launched its #ChairShare campaign. The campaign featured more than 90 red, oversized Adirondack chairs in stores across Atlantic Canada, built by social enterprises across Nova Scotia that employ adults with disabilities. The chairs were presented in stores, at community events, on the Sobeys website, on the flyer, on social media, and across traditional media outlets (Harris, 2017).

Oversized red chairs are also used as advertising signs. The most famous example is undoubtedly the XXXLutz Austrian furniture store advertisement. The 30-meter red chair, recorded in the Guinness Book of Records as the world's tallest chair, has been installed in the parking space of almost every supermarket since 2004 (XXXLutz – Die Marke, 2023).

Seats as an essential element of the designed public space

The next group presented includes benches—seats, which are an essential element of the designed public space. Their colors are the leading element and give the place its unique character.

One of the most known examples is undoubtedly the arrangement of the riverfront park, The Red Ribbon - Tanghe River Park in Qinhuangdao, China, by Turenscape (2007). The main element of the park is the 500-meter-long illuminated structure - the "red ribbon," that serves not only as the seat along the promenade and the banks of the river but integrates visually different parts of the park. The red color of the fiberglass element is used here as a means of visual expression, communication, environmental interpretation, and orientation (Red Ribbon Park, 2023).

Red also dominates the unusual public space designed by Carlos Martinez and well-known artist-performer Pipilotti Rist (2005) in Swiss St. Gallen. The space, named Stadtlounge (City Lounge), is covered with a bright red grainy gum surface, reminding one of an elegant carpet that integrates separate interiors and backstreets into an indivisible whole. Also, the elements of space furniture - the seats, the sofas, and the tables are formed from the same material, creating unique character of the outdoor red lounge (City Lounge, 2017).

The following two park spaces are dominated by the color pink. The first is Gloria Molina Grand Park in Los Angeles (CA), designed by RIOS in 2012. Custom site furniture was created in a bright magenta that has come to be known as "park pink," playing a significant role in defining the park's identity. The furniture, which includes freestanding benches, café tables, and chairs, creates a community feeling of Southern California backyard (Gloria Molina Grand Park, 2012).

The second is June Callwood Park in Toronto (Canada), an unexpected pop of pink in the heart of a concrete area. It was built in 2014 and named in honor of the late journalist and social activist. The Puzzle Garden benches and surfaces are made of pink rubber (Mok, 2022).

Colorful seats have also become a distinctive complement to Vienna's MuseumsQuartier (MQ) (Austria). This famous architectural complex, which hosts exhibitions, concerts, dance performances, author evenings, and meetings of young people from all over the world, has become even more recognizable since 2002 when the architects from the PPAG group – Anna Popelka and Georg Poduschka – designed for the MQ space a seat known as "Enzi." The modular benches have been presented since 2003 in various colors – “swimming pool blue,” “pale pink,” “pistachio green,” “reclining red,” “cream-beige,” "almost FC Austria purple," “lemon yellow,” "lush meadow green," "ivory tusk white," "strawberry field red," "candy shop pink," "bathhouse blue," "mermaid," and “lime green.” Since 2008, the color of the benches to be placed in the MQ space in a given year has been the subject of an open online vote. Currently, Enzi and Enzo seats, manufactured from fully recyclable polyethylene, are also available for purchase in the MQ store and placed anywhere in the world. They can already be seen in e.g., Berlin, Madrid, Warsaw, and even Seoul (MuseumsQuartier Wien, 2024).

Conclusions and summary

Based on the research, it should be concluded that the seats' colors are very diverse and generally represent two main directions—blending in or standing out from the surroundings, depending on the function that a given bench is to fulfill in the space.

In the case of typical benches, the prevailing tendency is to harmonize them with the surroundings, especially in the vicinity of historic architecture. Because their superior feature is functionality and practicality, in most cases, their dominant colors are connected with their construction material - brown of wood, gray of stone or concrete, or black or green of metal. A specific subgroup here is

modular seats, which, although offered as a mass product, usually have a wide range of colors, giving the possibility of individualization.
Individual seats are unique accents in public spaces, and their expressive colors and/or unconventional forms often evoke extreme emotions among observers.
The colors of artistic benches are completely free and depend only on the creation of the artist who creates them. In the case of benches with a message, the colors are selected according to a specific code, which is immediately understandable - as in the case of "patriotic benches," referring to the national colors, or "equality" benches in the colors of the rainbow, or the meaning is understood only thanks to information campaigns.
Oversized benches occupy a special place in this group. Their impact in space is not only related to their color, which is often red, but primarily to their size.
In the case of seats designed as an important and sometimes even essential element of a public space, their color becomes the leitmotif of visual identification and gives the place character. Only one color is often chosen for those seats to increase the monochromatic effect in the space.

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COLOR DESIGN FOR SAFETY AND INCLUSION

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Abstract

The Italian Law No 227/2021, for the reorganization and simplification of the existing provisions on disability, aims at ensuring equal rights in both life and work. In the workplace, integration and inclusion are achieved through interventions that guarantee effective accessibility and usability of spaces, equipment, and products. About 8% of males and 1% of females in the European population suffer from partial color blindness. Currently, however, color blindness is not recognized as a disability condition; those suffering from this visual anomaly do not obtain special benefits, such as targeted job placements, or tax deductions for purchasing support devices. A worker with chromatic anomalies may be assigned a task where color recognition is a measure of prevention and safety. Choosing environments, products, and technologies designed according to a “design for all” approach can contribute to creating a safe environment for everyone: eliminating or mitigating barriers that make activities more difficult reduces the need for excessive effort that can lead to fatigue or injuries. INAIL, the National Institute for Insurance against Accidents at Work, has created a document dedicated to industrial environments focusing on the use of color in the visual coding of machine control devices to overcome some visual disabilities. This paper summarizes and introduces such a document.

Keywords: color design for all, safety at work, color blindness

Introduction

In Europe, approximately 8% of males and 1% of females are affected by partial color blindness. These values suggest not to neglect this “group of workers”, and highlight the importance of analyzing the work contexts in which these individuals may be exposed to risks or, simply, may find themselves in unfavorable conditions. Currently, color blindness is not recognized as a disabling condition, and therefore those who suffer from this visual anomaly cannot benefit from targeted placement (provided only for those with a disability percentage of at least 46%), nor can they benefit from tax deductions for the purchase of any type of auxiliary device. However, a worker with color vision anomaly may be assigned a task in which color recognition is a prevention or a safety measure. The purpose of this work is to highlight the risks due to color blindness, and to focus on the technical and organizational measures that can reduce this risk in specific work contexts. In particular, this paper will consider industrial environments where the worker interfaces with machine control devices equipped with visual emergency and usage signals, for which a color-based coding is defined.

Color vision and anomalies

Color vision is the ability to discriminate objects based on the wavelengths of light they reflect. Color vision generally occurs in two stages: firstly on the retina, while the second can be defined as postretinal. On the retina, color perception involves specialized receptors called cones. There are three types of cones, depending on the wavelength to which they are sensitive. There are cones called S

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(short), more sensitive to short wave lengths; those called M (medium), with a greater sensitivity to medium wavelengths, and those called L (long), sensitive to long wave lengths (fig.1). Dyschromatopsia, also known as Daltonism (after the famous chemist Dalton, who was the first to study the anomaly from which he himself suffered), is the alteration of chromatic perception due to the lack or alteration of one of the three cones. Dyschromatopsia can compromise the safe performance of the work activity because, by altering workers' visual abilities, it can become a source of errors. According to the classic definition given by Von Kries in 1897, dyschromatopsia can be divided into four categories [1]. The two categories of interest for this paper are a*nomalous trichromacy* (protoanomaly, deuteroanomaly, tritanomaly), and *dichromia* (protanopia, deuteranopia, tritanopia). A*nomalous trichromacy* represents the mild form of dyschromatopsia and occurs when one of the three photopigments is altered. In this case, trichromatic vision is not totally compromised, but there is a reduction in sensitivity to the primary colors: red, green and blue.There are three cases: *protoanomaly* (fig.2, left), when the L cone moves towards the M cone, só that there may be difficulties in the reds. *Deuteroanomaly* (fig.2, right), when the M cone moves towards the L cone originating difficulties in the greens. *Tritanomaly,* when the S cone is anomalous, and difficulty in distinguishing blue, yellow and violet arises. The *dichromias* (or pure color blindness) are *protanopia*, *deuteranopia* and *tritanopia*. *Protanopia* is when the L cone is absent with red blindness; *deuteranopia,* when the M cone is absent with green blindness (fig.3). *Tritanopia,* when the S cone is absent: the subject confuses red-green; it is the rarest form (about one case in 10,000 people).

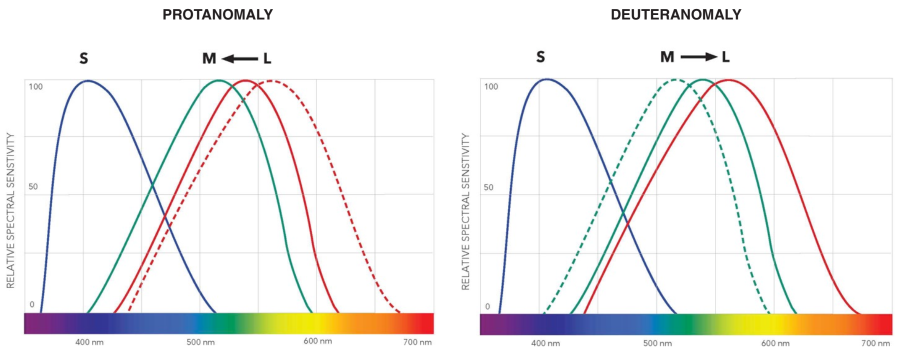

Fig.2 Anomalous trichromacy: alterations of the absorption curves in cases of protanomaly and deuteranomaly

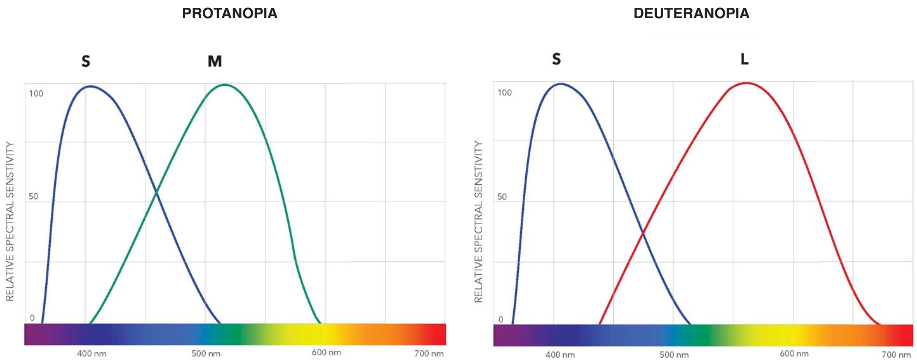

Fig.3 Dichromacy: examples of alterations of absorption curves in cases of protanopia and deuteranopia

Table 1 shows that the most numerous cases of color blindness are due to protanomaly and deuteranomaly; in these cases, the differences in green and red, are perceived only if the colors are very saturated. The most common form is Deuteranopia and it affects males much more often.

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Color coding in control devices

The guide to the Machinery Directive 2006/42/EC, in sections 1.7.1.1, “Information and warning devices” and 1.7.1.2 “Alarm devices”, refers to the relevant standards of the EN 61310 series, which contain specifications for control device design. Standard EN 61310-1 describes visual, acoustic, and tactile methods for indicating information related to safety, human-machine interfaces, and exposed individuals.

TYPE OF ANOMALY	% IN MALES	% IN FEMALES
Abnormal trichromia		
Protanomaly	1.08	0.03
Deuteranomaly	4.63	0.35
Tritanomaly		
Dichromia	Like tritanopia	Like tritanopia
Protanopia	1.01	0.01
Deuteranopia	1.27	0.01
Tritanopia	0.01	0.01

Table 1 - Incidence of anomalous Trichromia and Dichromia in the world population (MP Simunovic, M. Colour vision deficiency. https://doi.org/10.1038/eye.2009.251)

It emphasizes that all safety signage must be designed to ensure its meaning is clear and unambiguous.The standard establishes a coding or systematic representation of certain signals that must comply with a set of defined rules to facilitate the safe use and monitoring of machinery. Establishing rules to assign a particular meaning to certain visual, acoustic, and tactile indications helps ensure rapid recognition of control status and the position of actuators.The visual code is one of the means used for encoding indications (together with or as an alternative to acoustic and tactile codes) and can be expressed through color, shape, position, and variations in characteristics over time (e.g., intermittence). The use of color and intermittence are the most effective visual means for drawing attention. Color, in its hue dimension (the standard uses "color" to refer to hue), is thus considered the most effective visual coding method because it is more quickly decodable [3]. In fact, it is used as a priority choice for safety messages according to a standardized coding (Table 2) and is widely applicable and known.

COLOR	MEANING		
	Safety of people or of the environment	Conditions of the machinery or of the Process	State of the equipment
Red	Danger	Emergency	Broken down
Orange/Yellow	Warning/ Attention	Abnormal	Abnormal
Green	Safety	Normal	Normal
Blue	Meaning of obligation		
White Grey Black	No specific meaning attributed		

Table 2 - CEI EN 60073 Meaning of colours for coding

This implies that the color must be easily identifiable and distinguishable from the background and all other assigned colors; hence, one must consider its recognizability by operators with color vision deficiencies. This attention is required by technical standard EN 60073, which recommends, when employing individuals who cannot distinguish colors well, the use of additional means of coding beyond color. Specifically, when the message pertains to the safety of people, property, and the environment, it requires the use of additional coding methods, as generally outlined in standard CEI EN 61310-1 (Table 3) [4]. Only in this case, therefore, is the requirement of comprehensibility met even for workers with color vision deficiencies. The use of supplementary means and their respective coding is also foreseen when the message pertains to the state of the equipment or the condition of the process. It is evident that, at the time of purchasing the machine, the sensory capabilities of all its intended users are not always known, and it is well-recognized that the likelihood of a worker having such deficiencies is not so remote, particularly in milder cases (Protanomaly and Deuteranomaly). In any case, the documentation associated with the machine must provide sufficient guidance to ensure that individuals who need to read, interpret, and respond to such codes receive appropriate instructions (Clause 5.1 of the EN 61310-1 standard) [5]. It is therefore advisable to consider a visually impaired user during the design phase (design for all).

MEANS SUPPLEMENTARY	**ELEMENTS**
Form	Characters (alphanumeric, pictograms, graphic symbols, lines) Shape (font type, size, stroke width) Structure (line type, shading, punctuation)
Position	Positioning (absolute, relative) Orientation (with or without reference system)
Time	Variation as a function of time (flashing): Brightness / color / form / position

Table 3 - CEI EN 61310-1 Coding by means supplementary to colour (visual codes)

Color in the visual code

The visual signal is a message communicated through brightness or contrast, shape, size, or position, in addition to color. Color must be specified by hue, lightness, and saturation, whose definitions are also referenced in standard CEI EN 60073. However, the standard provides guidance on the selection of the hue to be associated with commands, but none of the other characteristics necessary for precise color identification (saturation, brightness, or contrast). Specifically, the standard refers to ISO 3864 for precise definitions of surface colors, which is in turn referenced by UNI 7543_2. Both refer to the colorimetric system CIE 15.2:1996 and provide the chromatic and luminance coordinates allowed for colors used in safety signage for different materials (see section Chromatic Indications for Inclusion). A single indication regarding contrast is found in the provisions of standard EN ISO 13850, which states that the actuator of the emergency stop device must be *red*. If there is a background behind the actuator, as far as possible, the background must be *yellow* (4.3.6, EN ISO 13850) [7]. This clarification is very useful in general, but even more so in the presence of workers with protanopia and deuteranopia, who are always able to perceive yellow. Other guidelines are provided only for the colors used in safety signage or video displays: the CEI EN 60073 standard specifies that for safety-related purposes, colors must be bright, saturated, and high-contrast. Only in the case of low-priority information colors can be unsaturated. As will be better explained later, saturation is a very important aspect: except in rare cases of dichromia (e.g., protanopia), saturation can enable individuals to recognize colors.

Analysis of the impact of color blindness on a human-machine interface

Below, as an example, images are provided of the control system of a prototype developed as part of the SENERGY Inail BRIC ID 40 2019 project, entitled “Intelligent power-off of machine assemblies with wearable RFID systems” by the University of Pisa, the University of Perugia, the University of Salento, and the University of Modena and Reggio Emilia. Using the Dalton simulator included in the Color Tools software [2], images of the same prototype and its representative details were created to illustrate the color vision alterations associated with Protoanomaly or more severe conditions such as Protanopia (Fig. 8).

Fig.8 - Senergy Inail BRIC ID 40 project prototype under normal vision, protonomalous vision and protanopa vision

Fig. 8 clearly shows that the red of the stop button, as well as that of the emergency stop device, appears desaturated in the case of protoanomaly and completely neutral in the case of protanopia, making it less visible compared to the other buttons. A person with such visual characteristics would not be able, in the absence of codes (e.g., alphanumeric code, position, etc.), to recognize the stop control. The emergency stop device is distinguished only by its size (larger) and its separate position (Fig. 9). Shape and position aid in reading the emergency signal and facilitate quick recognition. Considering that machine stop times can be in the millisecond range, the speed of perception of the danger signal plays a crucial role in ensuring the required reaction times.

Fig. 9 - Emergency control – Comparison between normal, proto-anomalous and protanopa vision

Fig. 10 shows the comparison between normal, deuteranomalous, and deuteranopic vision of green buttons. It is evident how the illuminated *green power button* always appears highly visible in all three simulations. Light increases color saturation and enhances the contrast between the button and the background, aiding in the perception and differentiation of controls. Lighteness becomes crucial

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in color perception, especially when two colors that fall on confusion lines are placed next to each other (see Luminance and lightness section).

Fig. 10 - Bright button and color alteration

Color guidelines for the use of color in the control device

The CEI EN 60073 standard for surface colors refers to the ISO 3864 standard, which is cited by the UNI 7543_2 standard. In this work, reference will be made to the tables provided in the latter standard to define the chromatic coordinates and luminance levels allowed for the colors used in safety signage for different materials. To facilitate reading for designers and employers, the colors of the machine control buttons related to safety (red, green, yellow) have been translated using the color codes of the RAL CLASSIC system, which is commonly used for paints, powder coatings, and plastics. The suggested guidelines are useful for meeting the "signal comprehensibility" requirement for both individuals with normal color vision and those affected by mild forms of dyschromatopsia.

Hue and saturation

The UNI 7543-2 standard refers to the CIE 15.2:1996 colorimetric system and specifies that the chromatic coordinates of the colors used for safety signage are correct only if they fall within their respective reference polygons: V = green; G = yellow; R = red; B/N = white and black; B = blue. The closer the colors are positioned to the sail-shaped curve representing the CIE diagram, the more saturated they are, and therefore more perceivable even by individuals with visual anomalies. The R area includes the chromatic coordinates allowed for the red button shades (according to the UNI 7543-2 standard for safety signage). As an example, four reds with different saturation levels have been selected, identified with the corresponding RAL codes (Fig. 11). RAL 3000 is the furthest from the CIE curve, the least saturated, and consequently the least distinguishable by a person with anomalous trichromacy.

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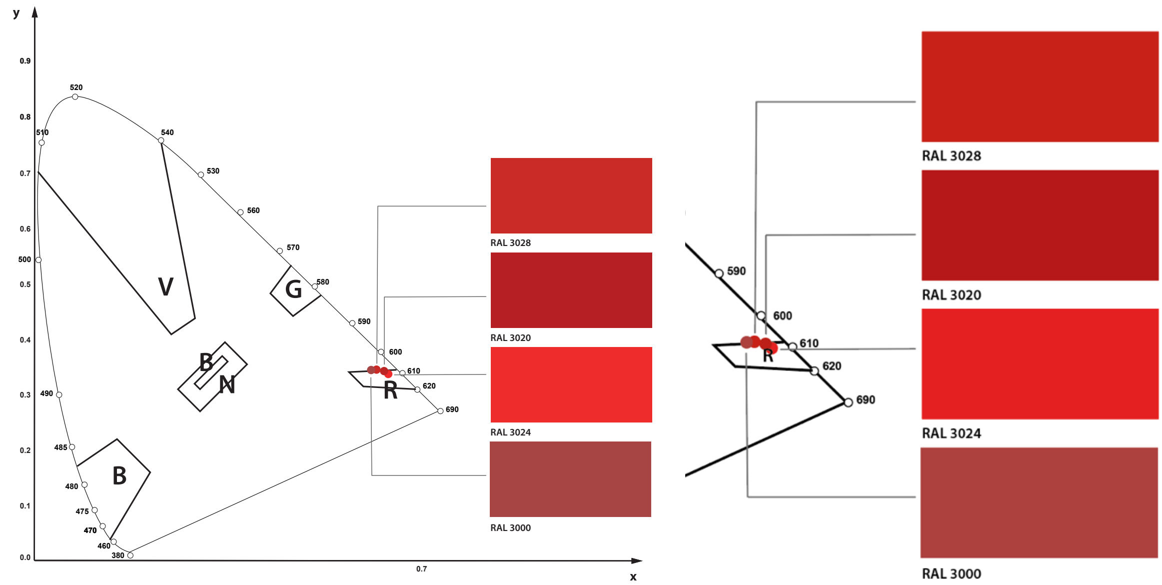

Fig.11 – Red - permitted colour coordinates and RAL codes

In contrast, RAL 3024, the closest to the curve in Fig. 11, is the most saturated and the most recognizable for people with anomalous trichromacy. Saturated color commands (made of ordinary materials) are much more distinguishable than commands made with less saturated colors. Fig. 12 simulates protanomalous, protanopic, deuteranomalous, and deuteranopic vision of two saturated colors (RAL 6038 vs. RAL 3024) and two less saturated colors (RAL 6032 vs. RAL 6032). The discrimination, between the two colors improves as saturation increases. In this research, yellow and blue commands are not analyzed because the percentage of people who suffer from genetic anomalies for these colors is very small (protans and deuteranopes perceive them correctly).

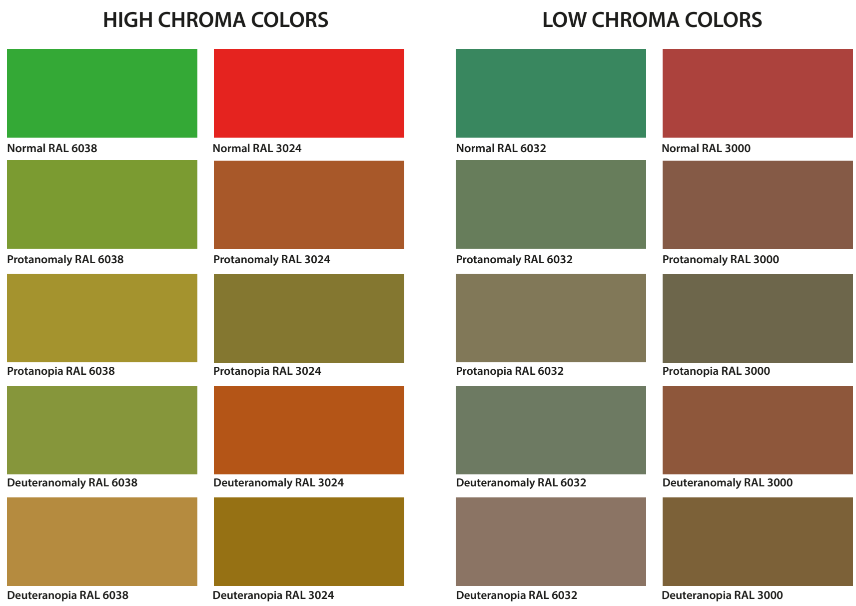

Fig.12 - Comparison between normal, proto-anomalous and protanopa vision of red vs green of different saturations

Luminance and lightness

Luminance is not represented in the two-dimensional CIE diagram; however, the UNI 7543-2 standard provides the minimum usable values for the luminance factor. Luminance contrasts (or lightness contrasts) help with color discrimination. Fig. 13 shows a green and a red along the protanopic confusion line [1]. Green and red appear identical to a protanope; by increasing the luminance of the green (Y 35 approx.) and keeping the red unchanged (Y 14 approx.), the ability to discriminate the colors along the same confusion line is improved.

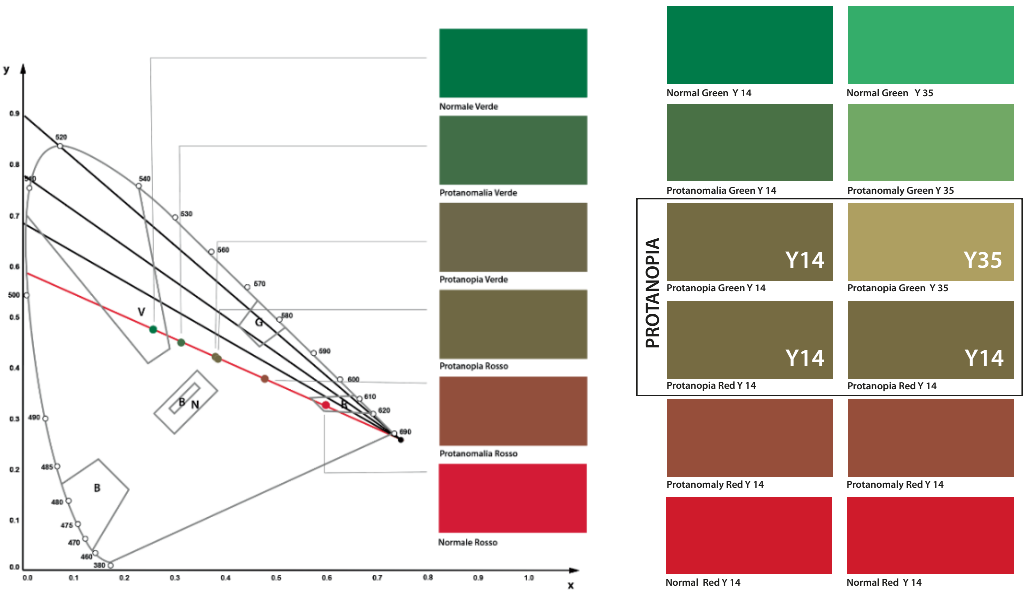

Fig. 13. Comparison under normal conditions, protanomaly, protanopia of one red and one green with the same luminance factor (Y=14) and of the same red with a second green with different luminance factor (Y=35).

Color vision anomalies and filter lenses

Recently, filtering lenses have become popular, which supposedly allow individuals with color vision anomalies to perceive colors. However, scientific analyses have shown that none of these glasses can restore accurate color perception to individuals with color vision deficiencies. The situation is different if the goal is to enable a person with anomalous color vision to recognize a particular signal.

In this case, it may be sufficient to use a filtering lens that lightens one signal and darkens the other. It is not plausible to manage the risks associated with machine use by color blind workers in this way: it is assumed that the tasks assigned are varied, and it is either unthinkable or impractical for the worker to wear filtering lenses only when reading a specific signal.

Acquired color vision abnormalities

Acquired anomalies can begin at any time after birth, with severity varying over time. They have similar incidence in both males and females, can affect only one eye, and may involve only a part of the visual field. The prevalence of the deficit is higher among older individuals due to the deterioration of the optic pathways. With age, the two main factors are the development of cataracts and the loss of sensitivity in the yellow-blue channel. Both factors lead to a loss of the ability to discriminate blue. This suggests to avoid dark blue colors, which, in older age, are often indistinguishable from black. This aspect is particularly important when considering the aging of the

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workforce in recent years (ISTAT) and, consequently, the attention required in risk assessment, considering the decline in functional abilities, especially physical and sensory, due to the natural aging process (Europe 2020 Strategy).

Color and incident light

The perceived color is a combined effect of emitted light (e.g., signaling light) and incident light (e.g., workplace lighting). Regardless of the presence of operators with color anomalies, environments, workstations, and passageways must be illuminated with natural or artificial light to ensure sufficient visibility (TU 81/08, Annex IV, 1.10.5). The EN 12464-1 standard provides guidelines for lighting design that meet visual comfort requirements and the visual performance of people with normal vision. It also provides qualitative and quantitative information on the main criteria determining the lighting environment and suggests considering ergonomic criteria, including visual capacity and color perception. As a general consideration, it is advisable to use lamps with a good color rendering index ($Ra \geq 80$) in work environments where color plays a significant role.

Conclusion

The interaction between worker and machine also occurs through the use of color, which is a priority visual signal for conveying safety messages. At the same time, given the significant prevalence of color vision anomalies in the population and the decline in sensory abilities associated with the aging workforce, it is not possible to ensure workplace safety by excluding people with color vision deficiencies from a large number of professions, especially those involving the use of machines. Inclusive design could eliminate the potential disadvantage. Standards provide guidelines in this regard, but they are often not specific. This work aims to emphasize that providing suitable work equipment also means providing equipment capable of reducing or eliminating disabilities related to color perception or facilitating safe work [8]. It is appropriate, in line with the principle of equity, to more precisely establish the minimum quantitative requirements for color adequacy to ensure the accessibility and usability of the work environment and equipment for workers with color vision problems.

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[4] EN 60073:2003-04 Basic and safety principles for man-machine interface, marking and identification - Coding principles for indicators and actuators

[5] EN 60204-1 Safety of machinery – Electrical equipment of machines – Part 1: General requirement

[6] CEI EN 61310-1 Safety of machinery - Indication, marking and actuation Part 1: Requirements for visual, acoustic and tactile signals

[7] EN ISO 13850 Safety of machinery - Emergency stop function - Principles for design

[8] UNI 7543-2 Safety Colours and safety signs – Colorimetric and photometric characteristics of materials

[9] D. Freda, F. Valan, A. Farini, L. Di Donato, M. Pirozzi, M.V. Zanoni, A. Ferraro, 2023. Sicurezza e inclusione. Analisi e indicazioni per l’uso del colore nel codice visivo dei dispositivi di comando macchine. ISBN 978-88-7484-836-2

The Enduring Economic Value of Color: Tracing its Multifaceted Impact Across Eras and Industries

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Abstract

Color, transcending its aesthetic appeal, has been a significant factor in shaping economic landscapes throughout human history, influencing trade, manufacturing, and cultural expression. This study explores the complex economic implications of color, tracing its influence from ancient civilizations to the present day, and its persistent relevance across diverse industries. The exploitation of color dates back to prehistoric times, with the use of natural pigments from minerals, plants, and animals for artistic and personal decoration. As societies advanced, the need for vivid and long-lasting colorants grew, leading to the evolution of more refined extraction and synthesis methods. The emergence of textile manufacturing during the medieval and early modern periods amplified the economic importance of color. The need for bright, fade-resistant dyes led to the expansion of dyeing centers and specialized guilds. The introduction of new dyestuffs, such as cochineal from the Americas and indigo from India, disrupted traditional trade routes and triggered economic changes. In the contemporary era, the economic implications of color extend beyond textiles to various sectors, including printing, painting, cosmetics, and food industries. The quest for environmentally friendly and sustainable colorants has become a significant economic catalyst, responding to increasing environmental concerns and consumer demands, spurring innovation, and opening new economic avenues. The study investigates the predictability of color's economic value, emphasizing the relative stability stemming from the fundamental human attraction to color and its psychological influence on consumer behavior, while recognizing the unpredictability introduced by disruptive forces, technological advancements, and evolving societal norms. It also scrutinizes the potential constraints of historical studies, such as cultural biases, quantification challenges, and the rapidly changing modern landscape. The study introduces mathematical models that strive to quantify the economic value of color, factoring in aspects like consumer preferences, target market size, product pricing, color differentiation, and brand value. These models aim to offer approximate estimates and insights into the potential economic impact of color choices in various product and market scenarios.

Keywords: economic value, color, culture, context, behavioural economics.

1. Introduction

Color has played a pivotal role in shaping economic and cultural landscapes throughout human history. Beyond its aesthetic appeal, the production, trade, and application of colorants have significantly influenced artistic expression, textile manufacturing, and various other industries, underpinning the economic fabric of civilizations across the globe (Garfield, 2002). The earliest evidence of color exploitation dates back to prehistoric times, with the use of natural pigments derived from minerals, plants, and animals for artistic purposes, such as cave paintings and body adornment (Abel, 2012; Cartechini et al., 2021). As human societies evolved, the demand for vibrant and durable colorants escalated, fueling the development of more sophisticated extraction and synthesis techniques. In ancient civilizations, the trade of natural dyes and pigments, such as indigo, madder, and Tyrian purple, emerged as a lucrative enterprise (Balfour-Paul, 2020). The acquisition of these rare and precious materials often involved complex trade networks, contributing to the economic prosperity of regions along the silk and spice routes. The scarcity and labor-intensive production processes of certain colorants, like the famed Tyrian purple derived from marine snails, rendered them symbols of wealth and status, driving their economic value (Steigerwald, 2002). The rise of textile manufacturing in the medieval and early modern periods further propelled the economic significance of color (Munro, 2003). The demand for vibrant and fade-resistant dyes facilitated the growth of dyeing centers and the establishment of specialized guilds. The introduction of new dyestuffs, such as cochineal from the Americas and indigo from India, disrupted existing trade patterns and sparked economic shifts, as regions with access to these resources gained commercial advantages (Serrano 2017). The 19th century marked a turning point with the advent of synthetic dyes, initiated by William Henry Perkin's accidental discovery of the first aniline dye, mauveine, in 1856 (Travis, 2001). This breakthrough paved the way for the rapid development of the synthetic dye industry, revolutionizing textile production, reducing manufacturing costs, and democratizing access to a wider range of colorants. The economic impact of this innovation was profound, as it facilitated the mass production of affordable, colorful textiles and fueled the growth of related industries, such as fashion and interior design (Bijker, 1993). Beyond textiles, the economic value of color extended to various sectors, including printing, painting, cosmetics, and food industries (Zollinger, 2003). The development of pigments, dyes, and colorants tailored to specific applications not only enhanced product quality and appeal but also drove innovation and created new economic opportunities. In the modern era, the pursuit of eco-friendly and sustainable colorants has emerged as a significant economic driver, responding to growing environmental concerns and consumer demands (Blackburn, 2009). The development of bio-based dyes, natural pigments, and more efficient production processes has opened new avenues for economic growth while mitigating the environmental impact associated with traditional colorant production methods.

Throughout history, the economic value of color has transcended its aesthetic dimensions, shaping trade networks, driving technological advancements, and influencing cultural and societal norms. Its multifaceted impact continues to resonate in contemporary economies, reflecting the enduring allure and functional significance of color in human societies.

1.1 The economic value of color in modern times

In contemporary society, the economic value of color remains highly significant, driven by various factors. Firstly, the globalization of markets and the rise of consumer culture have heightened the demand for visually appealing and differentiated products across industries. In nowdays, color plays a crucial role in product branding, packaging, and marketing, influencing consumer perceptions and purchasing decisions (Labrecque & Milne, 2012). Companies invest substantial resources in developing distinct color identities and employing color psychology to evoke desired emotions and associations with their offerings. Furthermore, the advent of digital technologies and multimedia platforms has amplified the importance of color in fields like graphic design, advertising, and content creation (Arnkil, 2013; Bortolotti et al., 2023). The ability to reproduce accurate and vibrant colors is essential for seamless cross-platform experiences, driving the development of advanced color management systems and calibration techniques. In the textile and fashion industries, color remains a vital differentiator, with seasonal color trends and consumer preferences shaping production cycles and economic dynamics (Soysal & Krishnamurthi, 2012). The pursuit of novel and sustainable colorants has prompted significant investments in research and development, aiming to address environmental concerns while meeting evolving market demands. Moreover, the economic value of color extends beyond aesthetic considerations, as color science and technology have applications in diverse sectors. For instance, in the field of security printing, specialized inks and pigments are employed to prevent counterfeiting, safeguarding economic interests (Kaminska, 2020). In the food industry, color additives and natural colorants play a crucial role in enhancing product appeal and meeting regulatory standards (Delgado-Vargas et al., 2000). The growing awareness of color accessibility and inclusivity has spawned new economic opportunities. The development of assistive technologies, such as color-blindness filters and accessible design solutions, caters to diverse user needs, fostering inclusivity and expanding market reach (Geddes et al., 2022). Lastly, the economic value of color is closely tied to its cultural significance and artistic expression. The preservation and promotion of traditional dyeing techniques, artisanal textiles, and indigenous color practices contribute to the preservation of cultural heritage and the growth of niche markets catering to discerning consumers (Brooks, 2015). In a world where visual appeal, branding, and user experience are paramount, the economic value of color remains a driving force, shaping industries, influencing consumer behavior, and fostering innovation in various sectors.

2. Predictability of the economic value of color

While the economic value of color has been a consistent thread throughout history, its future trajectory is subject to various factors that influence its predictability. On one hand, certain aspects of color's economic significance exhibit relative stability and continuity, allowing for reasonable forecasting. On the other hand, disruptive forces, technological advancements, and shifting societal norms introduce elements of unpredictability.

Behavioral economics, which explores the psychological factors influencing economic decision-making, provides valuable insights into the economic value of color (Bortolotti, 2023). The fundamental human attraction to color and its psychological impact on consumer behavior are deeply ingrained, suggesting a degree of predictability in color's role in branding, marketing, and product appeal (Singh, 2006). For instance, colors can evoke specific emotions and associations, through its unconscious semantic meaning (Bortolotti et al., 2024a); influencing consumer preferences and purchasing decisions in different context (Bortolotti et al., 2024b). Companies are likely to continue investing in color research and strategic color applications to gain competitive advantages in the marketplace. Additionally, the growing emphasis on sustainability and eco-friendly practices in the production of colorants and dyes provides a predictable trajectory. As consumer demand for environmentally responsible products increases, the economic value of sustainable color solutions, such as natural dyes, bio-based pigments, and closed-loop dyeing processes, is expected to rise (Samanta & Agarwal, 2009). However, the predictability of color's economic value is challenged by the rapid pace of technological advancements. Innovations in fields like digital printing, display technologies, and color reproduction systems can disrupt existing color workflows and create new market opportunities (Sharma et al., 2023). The emergence of novel color technologies, such as structural colors or tunable color materials, may introduce unforeseen applications and economic implications. Cultural shifts and evolving societal norms can influence color preferences and perceptions, impacting economic dynamics in industries like fashion, design, and art. The rise of global color trends, influenced by social media and pop culture, can introduce unpredictable cycles of color popularity, affecting production and marketing strategies (Bortolotti, 2023). Geopolitical factors and trade dynamics also contribute to the unpredictability of color's economic value. Disruptions in supply chains, tariffs, and restrictions on the movement of raw materials or finished goods can significantly impact the availability and costs of colorants, potentially reshaping economic landscapes. Moreover, the increasing emphasis on color accessibility and inclusive design practices introduces new considerations for predictability. As societies become more attuned to the needs of individuals with color vision deficiencies or cultural differences in color perception, the economic value of accessible color solutions may evolve in unexpected ways (Geddes & Flatla, 2022).

While certain aspects of color's economic value exhibit relative predictability, disruptive forces, technological breakthroughs, and societal shifts continually introduce elements of uncertainty. Effective forecasting and adaptation to these dynamic factors will be crucial for industries and stakeholders seeking to capitalize on the enduring economic significance of color.

Behavioral economics provides numerous insights into how color choices can influence consumer behavior. For instance, bright and warm colors like red, orange, and yellow are often used in retail environments to stimulate impulse buying. These colors create a sense of urgency and excitement, encouraging consumers to make quick purchasing decisions (Bortolotti et al., 2022). Companies also

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use specific colors to create and reinforce their brand identity. Blue, for example, is often associated with trust and reliability, which is why many financial institutions and tech companies incorporate it into their logos and branding (Labrecque & Milne, 2012). This strategic use of color helps to build a consistent and trustworthy image in the minds of consumers. In a crowded market, colors are used to differentiate products. Apple, for instance, employs sleek, minimalist colors like silver, space gray, and gold to convey a sense of luxury and sophistication, setting their products apart from competitors (Hagtvedt & Brasel, 2017). This differentiation through color helps to attract a specific target audience that values elegance and high quality. Cultural preferences also play a significant role in color choices. Different cultures have varying associations with colors, which can influence consumer behavior. For example, while white is often associated with purity and weddings in Western cultures, it is linked to mourning in some Eastern cultures. Companies tailor their color choices to align with these cultural preferences to better appeal to their target markets (Madden, Hewett, & Roth, 2000).

Seasonal marketing is another area where color choices are strategically employed. During the holiday season, green and red are prominently featured in marketing campaigns to evoke the festive spirit of Christmas. In contrast, pastel colors are used in spring marketing to convey freshness and renewal (Puccinelli et al., 2013). These seasonal color choices help to create a connection with consumers and enhance the effectiveness of marketing efforts.

Colors can also evoke specific emotional responses that influence consumer behavior. Green, for example, is often associated with nature and health, making it a popular choice for brands promoting eco-friendly or health-related products (Elliot & Maier, 2014). By leveraging these emotional associations, companies can create a stronger connection with their audience and drive consumer preferences. Gender preferences have traditionally influenced color choices in marketing. Pink is often used in products and marketing aimed at women and girls, while blue is used for men and boys. However, these associations are evolving, and companies are increasingly using gender-neutral colors to appeal to a broader audience (Cunningham & Macrae, 2011). This shift reflects changing societal norms and the growing recognition of the importance of inclusivity in marketing.

3. The complexity of the economic value of color

As we can imagine, predicting the economic value of color is a complex task that involves various factors and can vary across industries, products, and target markets. However, one possible formula that can provide a rough estimate is the following:

Economic Value of Color = (Color Preference Score × Target Market Size × Product Price) + (Color Differentiation Factor × Brand Value)

The economic value of color can be influenced by various factors, including consumer preferences, cultural associations, and market trends. While there is no definitive mathematical formula to predict this value, researchers have attempted to model and quantify the impact of color on economic outcomes through various approaches. One such approach is based on the concept of willingness-to-pay (WTP), which measures the maximum amount a consumer is willing to pay for a product or service. A study by Hagtvedt and Patrick (2008) proposed a model that incorporates color as a factor influencing WTP. The model suggests that the perceived value of a product can be expressed as a function of its intrinsic value (based on functional attributes) and the perceived value derived from its color. The formula can be represented as:

Perceived Value = Intrinsic Value + f(Color)

Where *f(Color)* represents the additional value contribution derived from the color of the product. This formula suggests that the perceived value of a product can be enhanced or diminished by the color associated with it, depending on the specific context and consumer preferences. For example,

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in the luxury goods market, certain colors like red or gold are often associated with higher perceived value and luxury (Hagtvedt & Patrick, 2008; Labrecque & Milne, 2012). As a result, consumers may be willing to pay a premium for products featuring certain colors, even when the intrinsic functional attributes remain the same. A recent example of this phenomenon can be observed in the introduction of a new color option for a popular smartphone model. Despite the lack of significant functional differences from other color options, this new variant has garnered significant attention and perceived value among consumers, potentially influencing their willingness-to-pay for this particular color variation. Another example can be seen in the automotive industry, where certain car colors are often associated with higher resale values. For instance, limited edition colors or unique paint finishes can make a vehicle more desirable, leading consumers to pay a premium for these options. This demonstrates how color can significantly impact the perceived value of a product, even in the absence of functional differences. It's important to note that the economic value of color is highly context-dependent and can vary across different product categories, cultural contexts, and consumer segments. Additionally, other factors like associations, marketing strategies, and personal preferences may also influence the perceived value of color in specific scenarios.

4. Conclusions

While the economic value of color has been a consistent thread throughout history, its future trajectory is subject to various factors that influence its predictability. On one hand, certain aspects of color's economic significance exhibit relative stability and continuity, allowing for reasonable forecasting. On the other hand, disruptive forces, technological advancements, and shifting societal norms introduce elements of unpredictability. Firstly, the fundamental human attraction to color and its psychological impact on consumer behavior are deeply ingrained, suggesting a degree of predictability in color's role in branding, marketing, and product appeal (Singh, 2006). Companies are likely to continue investing in color research and strategic color applications to gain competitive advantages in the marketplace. Additionally, the growing emphasis on sustainability and eco-friendly practices in the production of colorants and dyes provides a predictable trajectory. As consumer demand for environmentally responsible products increases, the economic value of sustainable color solutions, such as natural dyes, bio-based pigments, and closed-loop dyeing processes, is expected to rise (Samanta & Agarwal, 2009). However, the predictability of color's economic value is challenged by the rapid pace of technological advancements. Innovations in fields like digital printing, display technologies, and color reproduction systems can disrupt existing color workflows and create new market opportunities (Bortolotti, 2023). The emergence of novel color technologies, such as structural colors or tunable color materials, may introduce unforeseen applications and economic implications (Kinoshita & Yoshioka, 2005). Furthermore, cultural shifts and evolving societal norms can influence color preferences and perceptions, impacting economic dynamics in industries like fashion, design, and art. The rise of global color trends, influenced by social media and pop culture, can introduce unpredictable cycles of color popularity, affecting production and marketing strategies. Geopolitical factors and trade dynamics also contribute to the unpredictability of color's economic value. Disruptions in supply chains, tariffs, and restrictions on the movement of raw materials or finished goods can significantly impact the availability and costs of colorants, potentially reshaping economic landscapes (Bortolotti et al., 2023). Moreover, the increasing emphasis on color accessibility and inclusive design practices introduces new considerations for predictability. As societies become more attuned to the needs of individuals with color vision deficiencies or cultural differences in color perception, the economic value of accessible color solutions may evolve in unexpected ways.While certain aspects of color's economic value exhibit relative predictability, disruptive forces, technological breakthroughs, and societal shifts continually introduce elements of uncertainty. Effective forecasting and adaptation to these dynamic factors will be crucial for industries and stakeholders seeking to capitalize on the enduring economic significance of color.

4. Limitations

This study heavily relies on historical records and documentation to trace the economic significance of color over time. However, the availability and reliability of such data may be limited, especially for ancient civilizations or periods with scarce written records. This limitation could result in gaps or potential inaccuracies in the analysis. Additionally, the economic value and perception of color can vary significantly across different cultures and regions. By predominantly focusing on certain cultural perspectives or geographical areas, this study may inadvertently exhibit biases, leading to an incomplete or skewed understanding of color's economic impact.

Moreover, the economic value of color is influenced by a multitude of interrelated factors, including technological advancements, trade networks, societal norms, and consumer preferences. Attempting to isolate and analyze the specific impact of color on economic dynamics may oversimplify the complex interplay of these factors, potentially leading to oversights or inaccuracies. Quantifying the precise economic value of color across different industries and time periods is challenging. Many economic impacts may be indirect or difficult to measure, such as the influence of color on consumer behavior or the value of cultural heritage associated with traditional dyeing practices. Relying solely on quantitative data may fail to capture the full breadth of color's economic significance.

Analyzing the economic value of color requires an interdisciplinary approach, drawing from fields such as history, economics, anthropology, art, and science. This study may lack the depth or expertise required in certain disciplines, potentially leading to oversimplifications or gaps in understanding. The interpretation and analysis of historical data and economic trends related to color may be subject to personal biases, assumptions, or theoretical frameworks employed by the researchers. Different perspectives or methodologies could lead to alternative conclusions or highlight different aspects of color's economic value.

To mitigate these limitations, future studies could incorporate a broader range of cultural perspectives, employ rigorous interdisciplinary collaboration, and utilize advanced data analysis techniques to capture the nuances and complexities of color's economic impact across various contexts and time periods.

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Kawésqar colour names and their associations: survey results

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Abstract

The Pueblo Kawésqar Foundation presented an exhibition at the Ethnographic Museum of the University of Zurich, Switzerland, in 2023. It was accompanied by meetings, talks and workshops led by native Kawésqar people from the southernmost region of Chile. Since the mid-1970s, Chilean ethnolinguist and professor Oscar Aguilera (1949-2024) and Kawésqar anthropologist José Tonko worked closely together to rescue and revitalise the orally transmitted Kawésqar language and culture. In 1998, an alphabet with its phonetic transcription was established and officially recognised. As to the Kawésqar colour terms, seven colour names were found in the 2005 Concise Spanish-Kawésqar dictionary: a single term for green/blue, red, orange, yellow, black, white and golden/shiny. A survey conducted during the exhibition included twelve participants coming from the south of Chile, aged between 11 and 67. The interwievees were asked: "What are your personal associations with the Kawésqar colour terms?" This article aims to explore the individual relationship to colours as a starting point to discuss and understand the results within a larger context.

Keywords: colour terms, associations, Kawésqar people, Southern Chile, survey results.

Introduction

The Kawésqar people are native to the *Magallanes y La Antárctica Chilena* Region (colloquially also known as Western Patagonia) and are one of the eleven ethnicities recognised by the Chilean state in 1993. For several thousand years the Kawésqar lived in harmony with nature in the western Patagonian archipelagos extending from the Gulf of Penas to the Strait of Magellan. These marine nomads were skilled canoeists and hunters at sea and on land. They built their temporary dwellings out of oak or cinnamon branches covered with leafy twigs and sea lion skins. They were also skilled weavers of reed baskets (Aguilera 2022). Colonisation in the late 19th and early 20th centuries abruptly changed their lives as they were killed, leaving today about 500 survivors and only a few people who speak Kawésqar as their mother tongue. The academic interest of anthropologists and linguists led to the documentation and rescue of the Kawésqar language and culture. In 2023, the Pueblo Kawésqar Foundation (www.pueblokawesqar.cl) presented an exhibition at the Ethnographic Museum of the University of Zurich, supported by the Chilean Embassy in Switzerland, and accompanied by meetings, talks and workshops.

Survey methodology

A qualitative method was applied for this research and data-gathering entailed an open-ended interview question that allowed to collect free-form and unrestricted responses. The survey did not provide pre-set answer options. The interwievees were asked a single question: "What are your personal associations with the Kawésqar colour terms?"

The survey was conducted with twelve Kawésqar participants of the 2023 encounter and exhibition at the Ethnographic Museum in Zurich, in July and August. Aged 11 to 67 years, they were born in the south of Chile and are residents of the regional capital of Punta Arenas, Puerto Natales and the remote village of Puerto Edén. As to the gender, 4 male and 8 female persons participated in the survey that was conducted in Spanish and translated into English. This research aims to explore the individual relationship to colours as a starting point to discuss and understand the results within a larger context.

Colour terms

Linguistic documentation dates back to the 17th century. Chilean ethnolinguist and professor Oscar Aguilera (1949-2024) distinguished between two types of documentation. First, the informal one, which consists of data collected by early foreigners, geographers, naturalists or missionaries after the first Europeans navigated the Strait of Magellan in 1520, and second, the modern linguistic research that began in the 1970s. The first-mentioned documentation consists of word lists and some sentences. For example, Paul Hyades noted, ‘While recording the customs of the natives, Mr Bridges [1866] devoted himself, with real passion, to the study of their language. [...] The language possesses a considerable number of words, 30,000 at least.’ (Hyades 1884) Modern researchers, however, found that a considerable number of entries are inaccurate. Comparison of these informal records confirms, however, that only one language is spoken in western Patagonia, with at least two dialects, both of which are mutually intelligible. In 1966, in an international conference supported by the Wenner-Gren Foundation and the Smithsonian Institution, Kawésqar was listed as an endangered language that needed urgent documentation (Aguilera 2009). Kawésqar is one of the seven languages that constitute Fuegian linguistics (Clairis 1997).

Oscar Aguilera established an alphabet with its phonetic transcription, which was officially recognised in 1998. Since the 1970s, Aguilera and Kawésqar anthropologist José Tonko has been closely working together to rescue and revitalise the orally transmitted Kawésqar language and culture. In their Concise Spanish-Kawésqar dictionary (Aguilera and Tonko 2005) seven colour terms were found (Fig. 1):

Kawésqar	Spanish	English
arxa	verde/azul	green/blue
kejero	rojo	red
ánate	naranja	orange
t'alk'iase	amarillo	yellow
awókans	dorado/brillante	golden/shiny
akiefkiar	blanco	white
samán	negro	black

Fig. 1 – Kawésqar colour terms, with Spanish and English translations

Noteworthy is that Kawésqar do not have separate words for blue and green, but uses a single term, in English referred to as ‘grue’, *arxa* (green/blue). The colour terms *kejero* (red), *ánate* (orange), *t'alk'iase* (yellow), *akiefkiar* (white) and *samán* (black) are included in the basic colour terms as described by Brent Berlin and Paul Kay (Berlin and Kay 1969). Additionally, *awókans* (golden/shiny) is considered a colour term.

Survey results: colour associations

The associations with *arxa* (blue/green) mostly relate to the sea, but also to green forests, in particular to the canelo tree, and generally to the environment, nature and the earth (Fig. 3). The metaphors associated with this colour term are growth and the future, which are widespread. However, the association of blue/green with fire is rather exceptional. It could be explained by the use of gas stoves that produce blue flames (Fig. 2).

sea sea sea	dolphin	fjord forests green forest grass	environment (forest-sea)	nature nature	earth	growth	future	fire

sea sea sea as the sea the sea of Magellan		forest trees canelo (tree)							

Fig. 2 – Associations with blue/green.

Fig. 3 – Strait of Magellan (left), Puerto Natales Fjord (right). Photo: Margrit &. Beat Keller.

The associations of *kejero* (red) is mainly with fire. Local specificities are the Magellanic woodpecker the males of which have a red head and crest, as well as the guava berry (murtilla) and the fruits of the marshlands. Red is often associated with roses, but also with the heart, blood and passion. Seldom, however, it is associated with death (Fig. 4).

fire fire fire fire fire	sun	moon	the earth to paint one's face	woodpecker woodpecker (bird)	guava berry (murtilla) fruit of the peatlands	roses	heart	blood blood	passion	death

Fig. 4 – Associations with red.

The associations with *ánate* (orange) are interesting as they are related to the environment in which the natives live, such as the sunset or sunrise (Fig. 6), the fire, a local edible fungus that grows on the trees, the local flowers and the orange-coloured wood. Fruits imported from abroad are grapefruits and oranges. However, the metaphors of antiquity and oblivion are unusual (Fig. 5).

fire fire fire	sun	sunset sunset sunset	sunrise	pinatra (fungus) is eaten when it is fresh, well cleaned, cooked and dried fungus (pinatra) fungus digüeñe (fungus)	michay flower (local fruit-bush)	peat	salmon-coloured wood	bird's beak	grapefruit oranges	antiquity	oblivion

Fig. 5 – Associations with orange.

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Fig. 6 – Sunset in Torres del Paine National Park. Photo: Katharina Schindler.

The associations with *t'alk'iase* (yellow) are not surprising, as yellow is often associated with the sun, including the sunflower or other flowers such as the local calafate flower. The vast grassland, typical of the area, is only mentioned once with dried grass. The metaphor of falseness is also not very surprising. On the other hand, that yellow cannot be associated with anything is rather rare, perhaps due to the predominance of water, forests and snow in the landscape (Fig. 7).

sun sun sun sun midday sun	fire	flowers (calafate) calafate flower calafate blossom	colour of the stone flower	orchids	a sunflower	dried grass	autumn tree	falsehood	--

Fig. 7 – Associations with yellow.

The associations with *awókans* (golden/shiny) are absolutely interesting. With the exception of lust, this colour term is exclusively associated with natural phenomena and things, such as the embers, the light reflections on the surface of the water, the shimmering of fishes and stones in the water, the pyrite with which the natives once used to make fire, and the shining of the stars at night. It is also interesting that two persons found that there is no such a colour term (Fig. 8).

sun sun the sun	ember of fire	reflection on the sea at sunset reflection of the sun on the water reflection of the sun on the water reflection of the moon	fish fish	stars at night	stones in the sea	Pyrite stone	lust	[does not exist] [does not exist]

Fig. 8 – Associations with golden/shiny.

The associations with *akiefkiar* (white) are straightforward. White is associated either with snow and/or clouds (Fig. 10). White can also be associated with brightness and purity, but also with the moon or a white sheet of paper (Fig. 9).

snow snow snow snow snow snow snow	clouds clouds clouds cloud	moon	luminosity (claridad)	purity pure	sheet (paper)

Fig. 9 – Associations with white.

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Fig. 10 – Torres del Paine. Photo: Margrit & Beat Keller.

The associations with *samán* (black) are also very specific, because black is primarily associated with the night. Darkness can have a positive effect when resting, but it also has negative connotations when linked to bad spirits. The connection to the black clay with which the ancestors used to paint their bodies is interesting. This reference also occurs with red. The association with an animal, such as the grandfather's dog, is tangible.

night night night night night night	darkness	cave	black clay	coal	my grandfather's dog	rest	something bad evil spirits	negativity

Fig. 10 – Associations with black.

A few conclusive remarks

Several languages fail to have a distinction between green and blue and use a single term for both colours, blue and green. This is thus not a specificity of the Kawésqar language.

On the other hand, a dominance of colours with longer wavelengths (red, orange, yellow) is evident.

According to Eva Heller's research (Heller 1989), 53% of the research participants in Germany associate gold with wealth. However, this association is here not mentioned at all. Despite the forced radical change of life, the survey results show that still today the Kawésqar people remain closely connected to the local natural environment.

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Color and Education - Communication / Marketing

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Expanding color understanding in the graphic communications classroom through color model comparisons.

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Abstract

As an industry, graphic communications encompasses a wide range of visual technologies including computer generated imagery, graphic design, photography, print production, videography, brand management, and web development (Geisinger, Calkins, & Wilson, 2023). Color plays a significant role within all these segments of the industry. Due to technological advancements and evolving customer needs, graphic communications companies have adapted, and fewer traditional print companies define themselves solely as printers, but rather as marketing solutions providers. This means that they provide customer support and content management across all these visual channels. However, the way color information moves between mediums and how professionals communicate color remains siloed. Given the many different color models, their use within a specific segment of the industry, and the approach to defining color within that space, the challenge faced in education is teaching color in a way that spans across all the industry segments. For example, the same color can be notated in Cyan, Magenta, Yellow, and Black (CMYK) for a print professional or Red, Green, and Blue (RGB) for a digital designer or Hex numbers for a web developer. Today's students will become the future graphic communications professional, and they need to have a more comprehensive and transferable understanding of and language around color. This article bridges the gap between the various color models and languages so educators, professionals, and students can better communicate about and manage color in a medium-agnostic way while connecting the different color models to recognizable historical developments to promote student understanding and retention. This paper proposes a way to introduce and embed the history of color language and models into historical milestones, acknowledging the timing and reason for each development independently and within the broader context.
Keywords: Graphic Communications, Education, Color Models, Color Communication.

Introduction

Clients need their marketing materials and branding colors to be consistent across all platforms (e.g., video, print, and web) (Budelmann, Kim, & Wozniak, 2010; Jin, Yoon, & Lee, 2019). How color is communicated for each medium is different. In web or computer graphics, color is defined within a red, green, and blue (RGB) color space. With print production, color is defined in terms of ink–cyan, magenta, yellow, and black (CMYK). When measuring color consistency and accuracy in print, we use CIE LAB (Hunt & Pointer, 2011). Beyond these, there are a host of other color spaces that are used within the graphic communications industry including: CIE LUV, CIE CAMs (02 and 16), HSB/HSL, YIQ, LUTs, and Oklab/Oklch. CIE XYZ is an underlying common component across some, but not all of these models.

Color in history

Communicating color accurately has been important in many aspects of day-to-day life since early humanity. Gatherers needed a keen understanding of how to correctly identify food sources and color indicated the ideal time to gather produce. For survival, they passed that information down through younger generations by accurately describing the ideal timing for maximum nutrients by color. Early painters often worked with apprentices and the masters had to communicate to their apprentices very

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specific colors to block in new works and paint backgrounds. For example, even a single color of paint has dozens of different pigments, for example red paint options include Vermilion, Crimson, Carmine, Cadmium, etc. and these produce subtle or even dramatic differences in overall tone within a finished piece. More recently, brands have specified not only fonts and logos but also a set of colors that are recognizable to customers. In the product marketplace, there is a recognizable difference between Coca-Cola (PMS 484), Netflix (PMS 1795C), YouTube (PMS 2347 C), and McDonalds (PMS 485C) reds (Ho, 2015; US Brand Colors, 2024). Even though these colors are all close, a consumer will often be able to notice brand discrepancies when seen in context (Jin, Yoon, & Lee, 2019).

In the last hundred years consumption of visual media has rapidly evolved across many mediums requiring adjustments in how color is communicated to ensure consistency and accuracy. Both capture devices and final output options have expanded and so has the challenge of accurate representation of colors for content producers. Many organizations have worked to find mathematical solutions that define colors based on specific industry segments or even more broadly across different media but no single one of these models is universally adopted across all color communication today.

Meeting the challenges of teaching color

Students enrolled in a color class can come from a variety of different majors and backgrounds. Courses on aspects of color within a specific field are found in a wide range of programs including architecture, art, computer science, food science, graphic communications, horticulture, information design, material science, nursing, and psychology (Clemson, 2022). These students have diverse needs when it comes to understanding and communicating color and most do not have personal memories of the significant milestones in imaging that instructors could use to anchor these lessons. Educational models based on the constructivist theory encourage instruction to build from a student's personal experience and knowledge (Phillips, 1995). This theory of learning points to a learner's ability to gain new knowledge by connecting to something familiar. Building upon this educational theory, this paper shares a timeline approach that combines relatable historical events with print and digital color developments. This creates a story-based approach that helps students contextualize and remember new information (see Figure 1).

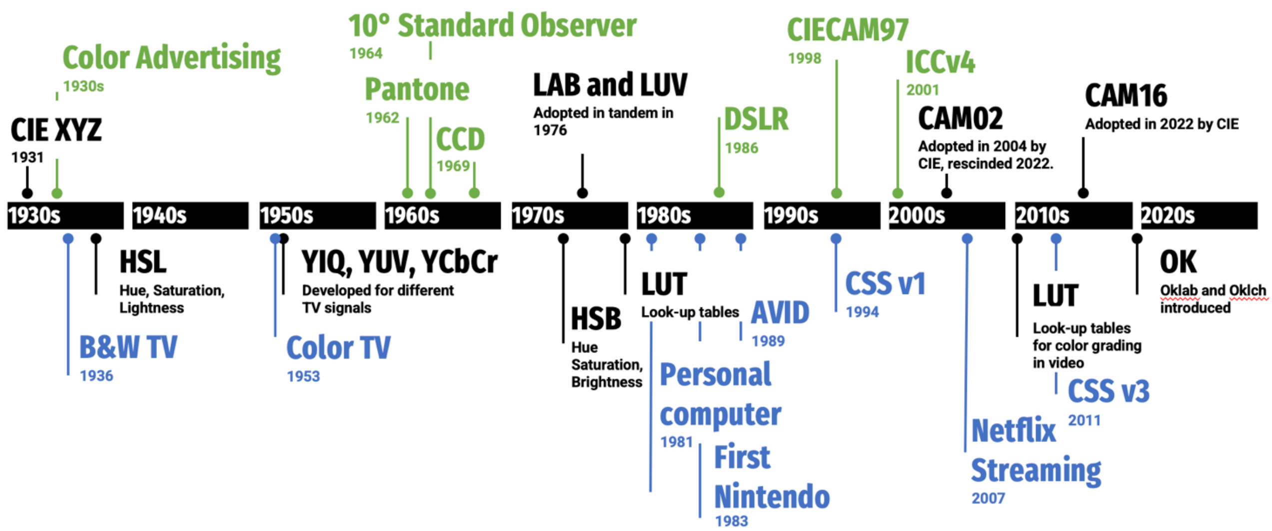

Fig. 1. Timeline of color development in graphic communications.

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Color models within historical context

1930s

In the mid-1930s, families and neighbors gathered around the first black and white television sets. Although video was still consumed in monochrome, color was becoming more common in print and photography. Color advertising in publications began in this decade and the first 35mm color roll film was also introduced. With the addition of color reproduction in magazines and newspapers, we needed to develop a more consistent way to measure, control, and communicate color.

In 1931 the International Commission on Illumination or CIE created the XYZ color space which became foundational for many color models and spaces (Ibraheem et al., 2012; Luo & Li, 2007). The data used to create the XYZ color model, referred to as the two-degree standard observer data, came from experiments in which individuals were asked to adjust the intensity of red, green, and blue light sources to best match a provided target. A two-degree field of view was used because it was believed then that it was only in this range where the cones in the eyes could sense color. Results were then averaged and thought to be a good representation of human color vision. The data collected within the experiments is still used within many color models and applications today. Utilizing illumination data, sample reflectance, color matching functions (Xbar=average red cone response; Ybar=average green cone response; and Zbar=average blue cone response), and a normalizing constant, the tristimulus products of XYZ are calculated (Ibraheem et al., 2012). XYZ exists within CIE Lab, CIE Luv, CIECAM02 and CIECAM16, as well as many other models.

HSL (hue, saturation, and lightness) was developed in the late 1930's to describe colors in a more human-centered way than RGB. It was difficult for a person to imagine the impact of a "little less red" in a color that is primarily green. In the HSL model, Hue (color) is defined as a number 0-360 degrees where red is 0 and 360 degrees–the color wheel begins and ends with red–and other colors are represented by a numerical between 0 and 360 degrees (PTC, Inc., 2023). This results in a cylindrical, 3-coordinate model with neutral tones running vertically in the center column (Sharma, 2019). S (saturation) defines the richness of the color where 0% represents flat gray and 100% indicates the brightest possible color in that hue. L (lightness or luminance) represents how brightly lit a color is from dark at 0% to brightly lit at 100%. This model is not absolute, meaning that to understand the exact color, you would need both the HSL information and the RGB space used. This model cannot stand alone to describe color like the XYZ-based LAB model does.

1950s

By the 1950s, 35mm color film was commonly accessible and affordable. Although the first feature length, silent color film–The World, The Flesh, and The Devil–was released in theaters in 1914, technicolor films did not become common until the late 1930s, and color television entered the market in 1953 (Britannica, 2024). With the introduction of at-home color television sets, a modification for how video was recorded and distributed became necessary.

While inkjet printing technology saw great advancement in the 1950's, the idea was not new. Theories on how to accomplish this type of printing developed as early as the 1800s (Le, 1998). However, advancements in inkjet technology were hampered by many challenges including poor quality reproductions, spread of liquid inks, color bleed, and absorption. Technology and substrates have advanced and now inkjet can produce high quality reproductions that expand beyond CMYK through extended or expanded color gamut (ECG) inks.

Although not a color model, YIQ and YCbCr are used to transmit light and color images from broadcast to televisions (PTC, Inc., 2023). Similar to other previous color models, YIQ and YCbCr separate out luma (luminance) from color which allows a single cable to be used for either black and white (luma only) or full color video for television. This can isolate and adjust the brightness information since in general, humans are more sensitive to intensity and luminescence than they are to color. This significantly compresses the visual information. For example, cameras capture in RGB and if we were sending TV content in that color space, it would require full resolution for each channel (R, G, and B values). However, the Y (luminance) is the only full resolution part necessary to translate high quality color video when converted back to RGB by the television for viewing (PTC, Inc., 2023). This system does convert in and out of RGB so it is important to keep gamut in mind to ensure colors stay within the range for display.

1960-70s

In 1963 Pantone Corporation introduced a new color system that would revolutionize not only printing but the whole graphic communications industry (Pantone, 2024). The Pantone Matching System (PMS) consisted of 500 colors that could be defined, communicated, and reproduced on the printing press. Building around the PMS system, companies developed their branding colors (e.g., Coke red is PMS 484). Today, the PMS consists of over 6,700 process colors which have moved beyond CMYK into ECG (which adds additional colors eg. red, blue, orange, green, violet) for print-based media. While primarily built for the printing industry, Pantone would develop and establish itself as a standard for color specification across media, covering everything from graphic design to fashion with their trademarked color swatch system.

In the 33 years that passed from the original CIE experiments, new understandings about human vision emerged showing that the human eye has a much wider field of view than initially thought. The CIE conducted the 1964 experiment again utilizing a 10-degree field of view. The results, called the ten-degree supplementary standard observer, were similar but revealed some deviations from the two-degree experiment. Both sets of results feed into the XYZ color model and are still utilized today.

In 1969, Bell Labs developed a charged-coupled device (CCD) (McLean, 2008). While initially developed as an element in computer memory, the light sensitive circuit could capture images. The CCD worked by breaking the captured images into pixels. With further developments, the circuit could capture higher quality images resulting in better reproduction (Hunt, 2004). While used in many other contexts, CCDs can be found in scanners, video cameras, and digital still cameras.

In 1976 both CIE LAB and CIE LUV were adopted by the Commission on Illumination (MacEvoy, 2005). These models were developed simultaneously by two groups who wanted a perceptually uniform color space. CIE could not make a recommendation on which model was better, thus adopted both. Both models are based on the fundamentals of lightness, chroma, and hue. In each model, L stands for lightness and ranges from pure black to pure white on a 0-100 scale. A and B, as well as U and V, represent chromaticity with no specified numerical limit. Chroma is defined as the colorfulness of a stimuli relative to the brightness of a similarly illuminated white (Hellwig & Fairchild, 2021), while hue defines the color itself. Within a color picker, A and U would represent the color that falls along the x axis ranging in color from green to red/magenta. B and V fall along the y axis ranging in color from blue to yellow. L or lightness is a third dimension and is adjusted up or down to select lighter or darker shades within the color gamut. Both CIE LAB and CIE LUV utilize the XYZ data as a foundation (MacEvoy, 2005). CIE LAB is the primary building block for color management within the printing industry and for the generation of International Color Consortium (ICC) profiles. ICC profiles are data driven color characterization profiles generated for a specified input or output device allowing for consistent color communication across devices and platforms. Designed around light measurements, filters, and optical systems, CIE LUV is used extensively in computer graphics and applications that involve colored lights including stage, video, and photographic lighting.

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1980-90s

These decades saw a rapid development of technology requiring new ways of communicating color. In 1981, the first personal computer arrived at market, completely changing how digital content would be displayed. Early computer monitors were monotone but by 1994, CSSv1 (Cascading Style Sheets) was published (World Wide Web Consortium, 2024 and Britannica, 2024). Designers could now create graphics for websites with color assigned for individual elements on screen. In 1983 in Japan and in 1986 in the United States, Nintendo took the world by storm with the original Nintendo Entertainment System (NES) (Kohler, 2010). Again, graphics were simplistic initially but as both gameplay and visual elements advanced, clear communication of color from the designers to the production artists became a necessity. In photography, the first DSLR (digital single lens reflex) camera became available, starting the movement away from film to images that could only be accessed via a computer screen (Britannica, 2024). At this point, most newspapers were printed in full color and digital printing advanced when the first digital printing press, the Indigo E-Print 1000, was developed by Benny Landa in 1993 (Landa, 2024).

The mid 1990's saw a transition in perspective on the development of color appearance models (Luo & Hunt, 1998). It was suggested that a single model should bridge the gap between the existing and future models. We needed a color appearance model for use within the entire imaging industry. The result was CIECAM97 which introduced a comprehensive approach to modeling. While the basis is still a linear transformation of the CIE XYZ data, the model worked in a wide range of intensities from low light to full sunlight and functioned effectively for a wide range of object (stimulus) intensities. This model considered viewing conditions and background, and it was the first model to be rendered for hue, brightness, lightness, saturation, chroma, and colorfulness. CIECAM97 was a transition model and immediately upon release updates and improvements were already underway (MacEvoy, 2005). This led to the development of CIECAM02.

The HSB color model was developed in 1974, shortly before the release of computers. Building on the HSL color model (1938), HSB was tailored to digital displays like computers and gaming systems. Unlike HSL, HSB uses brightness which is more similar to light than the L value in HSL. However, white is not the opposite of black in this model because the S (saturation) value impacts how brightness changes the hue. More specifically, for the B value 0% is black and 100% is white or a very well-lit hue depending on saturation value. To get true white you must set the brightness to 100% and the saturation to 0%, removing any hue from the color when fully lit (Sharma, 2019).

2000-10s

The first iPhone was released in 2007 and changed the way we view media from websites to photographs to video content (Britannica, 2024). Although some films and television shows are shot on film even today, non-linear editing was released in 1989 with the AVID system and by the early 2010's a large portion of video content was shot, edited, and distributed digitally. In 2007, Netflix pivoted from a DVD-by-mail subscription to a video streaming network marking a completely new distribution model for video. Video content could now be watched on-demand and on almost any screen size from a four-inch smartphone to a huge projection screen (Britannica, 2024). Website design also got a major upgrade in 2011, when CSSv3 was released which included new ways to specify colors–an expanded list of colors that can be identified by name, the ability to indicate colors using HSL, and the addition of an alpha channel that indicates transparency (World Wide Web Consortium, 2024). ICC v4 was introduced in 2001 to correct some ambiguity that existed in v2. This served to address inconsistencies across vendors who produced and used the profiles (World Wide Web Consortium, 2024). The changes and clarity in specifications of white point, colorimetric rendering, illumination, and chromatic adaptation has led to increased predictability and performance across platforms.

Building off developments to CIECAM97, CIECAM02 stems from CIE LAB but was a model proposed to represent a far more complex color phenomena requiring more starting information to compute (Hellwig & Fairchild, 2022). While CIE LAB focused on lightness, chroma, and hue, CAM02 expanded to six dimensions of color appearance including brightness (luminance), lightness, colorfulness, chroma, saturation, and hue (composition and angle). These changes more closely simulate how human vision perceives color under different lighting conditions (MacEvoy, 2005). Within CIE LAB, there were irregular color shifts where blues had a tendency to bend towards the violet tones which presents a challenge in some color formulation, development, and matching in the printing process. CAM02 was relatively successful at addressing this by utilizing more starting information including the surrounding luminance, background luminance, and other contextual factors, to better match human perception even using the same XYZ data for standardized illumination. In fixing the irregular color shifts, a new challenge had developed with print-based applications. With product packaging, the additional information required to calculate CAM02, mainly the surround and background luminance, changed for products from store to store and potentially even from aisle to aisle within a single store, thus making the consistency within print-based contexts impractical. On the digital side, CAM02 is often used behind the scenes utilizing the metadata and artist input to adjust the color in RAW (digital negatives) image editing.

Although Lookup Tables (LUTs) were developed in the 1970s to calibrate between different monitors, filmmakers began to use them heavily in the late 2010s as an alternative to ICC profiles within the filmmaking context (Srivastava, Ha, Delp, & Allebach, 2010). With LUTs, filmmakers could create consistent, yet diverse visual content by applying LUTs in post-production after standard color grading adjustments. There are 1D and 3D LUTs. 1D is a small file and maps a one-to-one conversion (can only remap one value such as luma or R). 3D LUTs remap each input to more than one output value and can also handle nonlinear translations (Hunt, 2004). So, one 3D LUT, although significantly slower to process, could apply various transformations across all the color and luma channels simultaneously. There are three types of 3D LUTs commonly used today—calibration (display accuracy), technical (conversion between color spaces), and creative. Creative or Look LUTs color grade everything to match a predetermined “look” across all the footage enabling a creator to ensure color and light consistency for the entire “world” of the film.

2020s and beyond

Research and development in the field of color science and color communication will continue. Despite developments from the past 90 years, we still have much to learn about how human vision functions and how to represent that vision across color models and mediums. As technology improves and new technologies are invented, we may see a need to expand the current modeling.

Adopted in 2022, CIECAM16 began in the mid 2010’s as a revision to CAM02 to improve the calculations for lightness, brightness, chroma, and colorfulness within the model (Melgosa, 2022). Calculations for CAM16 are identical to CAM02 after the chromatic adaptation transformation (CAT) (Hellwig & Fairchild, 2022). Given the complexity of the calculations and the additional data needed, CAM16 is used more on the digital side than in print-based applications. Photo editing software using this model allows for adjustments based on scene conditions (adaptation, surround, and luminance). Adjustments can be made with algorithms based on pairings such as lightness and chroma, lightness and saturation, or brightness and colorfulness. In addition, adjustments can be made with consideration of the final viewing environment with luminance, chromatic adaptation, temperature, tint, and environment.

CAM02 or CAM16 in a print-based context could allow for using standardized values as placeholders for some of the surround and background values. The potential challenge to adopting this could lie in the changes necessary for existing measurement technology (e.g., colorimeters, spectrophotometers, densitometers, etc.) and software applications. These changes would impact how devices agree on standardized values allowing them to function in a print environment. With CIE XYZ being the foundation for these models, the opportunity to expand is there.

Oklab and Oklch was introduced in the early 2020s to address weaknesses in previous color spaces and bridge the gap between perception and accuracy. Oklab uses the D65 white point, and the LAB values are represented the same as CIELAB and with Oklch the L=lightness, the c=chroma, and the h=hue. Oklab differs from CIELab in the calculations and in how it is converted from the XYZ coordinates. XYZ is not perceptually linear, so Oklab and Oklch adjust these calculations in an effort to align more with human perception of color resulting in simpler, faster calculations (Ottoson, 2020). Currently, this model is only well adopted in web development where it is the standard in CSSv4 (World Wide Web Consortium, 2024). However, Oklab and Oklch combine the strengths of CIE Lab and LCH and make additional improvements in computation efficiency and accuracy and because the hue is more linear, there are better gradients and smoother transitions between colors. Oklab and Oklch map a wider gamut than sRGB allowing them to leverage newer screen technology, P3 and P4, as it expands into the market (Ottoson, 2020).

Discussion and conclusions

Color is at the core of what we do within the graphic communications industry, but the siloed world of color makes presenting this information to students challenging. As educators, we have found the need to present a more contextualized background of color and color models to students. We propose that presenting this information embedded in history enables students to see the evolution and progression of color across various media. Through this, students might more clearly see that these are not siloed events or entities, rather these models have built off one another and have grown together to bring us to where we are today. Until a single unifying color model exists, the current mathematical models will continue to be developed and improved to meet the changing needs of the imaging industries and students will need to understand this broader application and context. Today’s students must be equipped to participate in the future development of and use these diverse models within their careers to ensure ongoing development towards models that address the needs of all stakeholders.

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Demonstrating Metamerism: A Key Concept for Lighting/Color Design Education

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Abstract

The phenomenon of metamerism, where two colors appear identical under one light source but different under another, is a fundamental concept in lighting design. This experiment aimed to provide a tangible demonstration of metamerism for students in lighting design education. A rectangular box was constructed to house two metameric color samples and two distinct light sources: a Philips TL-Mini standard 8W/33-640 fluorescent lamp and a Luxeon star LED. Students observed the color samples through a controlled lighting environment within the box via a viewing aperture. Under one light source, the samples appeared identical, while under the other, they exhibited noticeable differences. Two buttons on the side of the box allowed for independent activation of the light sources. An explanatory card was attached under the box, and a compartment at the back allowed for cable storage during transport.

Keywords: Metamerism, Lighting/Color Design, Design education, Color perception, Inductive teaching method.

Introduction

Metamerism is a phenomenon in color science where two colors appear identical under a specific condition but differ in their spectral compositions. This occurs because the colors produce the same response in the human visual system despite their different spectral characteristics. The term “metamerism” comes from the Greek words “meta” (beyond) and “meros” (part), indicating that the colors are beyond or different in their physical aspects but appear the same to the eye. This phenomenon is a result of how the human visual system processes colors. The human eye has three types of cone cells, each sensitive to different ranges of wavelengths : long (L), medium (M), and short (S), with the definition of the CIE standard chromatic observer from these values we can then obtain the known tristimulus values XYX (Fig. 1) These cones detect various colors and send signals to the brain, which processes them as different hues, saturations and lightness. Spectral power distribution describes how the intensity of light varies with wavelength. Different colors have unique spectral power distributions, but metameric colors have distributions that produce similar responses in the three types of cones. When two colors have different spectral power distributions but produce the same response in the visual system, they are considered metamers. Tere are four types of metamerism:

1. Illuminant Metamerism: this occurs when two objects match under one light source but not under another. For example, colors that appear the same under incandescent light may look different under daylight due to the variation in the spectral content of the light sources (Wright, 1929; Guild, 1931).
2. Observer Metamerism: this arises when two objects match for one observer but not for another. This can be due to differences in color vision between observers, such as colorblindness (Fairchild, 2013).

3. Geometric Metamerism: Occurs when two samples match in color under one viewing geometry but differ when observed at another angle or under different surface conditions (Hunter and Harold, 1987).
4. Field Size Metamerism: Occurs when two colors match when viewed in one spatial context (e.g., small areas) but not in another (e.g., larger areas) (Wyszecki and Stiles, 2000).

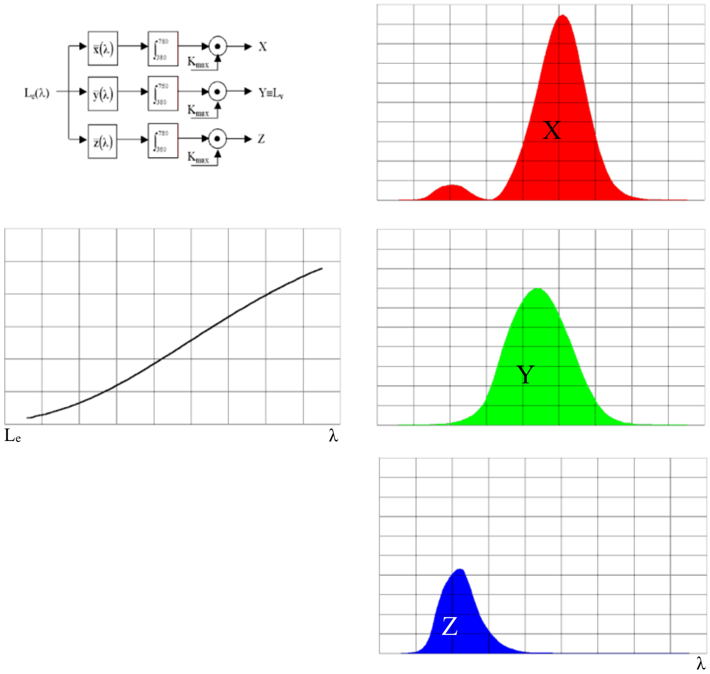

Fig. 1 - From the spectral radiance (incandescent lamp) to the tristimulus values (the areas under the three curves) the transformation is not biunivocal.

The phenomenon of metamerism was first explained in the context of human vision by early researchers in color science, particularly in the late 19th centuries. However, it is deeply rooted in the trichromatic theory of vision proposed earlier by Thomas Young, Hermann von Helmholtz and James Clerk Maxwel. These scientists demonstrated that the human eye perceives color through the combination of responses from three types of photoreceptor cells, which became the foundation for understanding metamerism. The formal study of metamerism and its implications for color science were later advanced significantly by William David Wright and John Guild in the 1920s and 1930s.

Nowadays metamerism has significant implications across various fields, including color science, manufacturing, and design. Controlling metamerism is crucial for ensuring product quality and maintaining color consistency. For instance, in textile and apparel industries, metamerism can affect the color matching of fabrics and accessories. In printing, colors in printed materials can look different under different types of lighting. Similarly, in automotive painting, metamerism can cause color mismatches between different parts of a vehicle. From an educational point of view, being able to demonstrate the phenomenon of metamerism caused by light sources is fundamental in the training of designers who will deal with lighting and color. The designed tool demonstrates to students that color and the vision of the world arund us is a psycho-perceptive sensation generated by the human mind with all the limitations of our visual system and metamerism is precisely an example of our limitations in trichromatic color vision. Novice lighting and color designers can draw from these findings to develop a deeper understanding of the subjective nature of the perception of lighting and color, allowing them to employ luminaries and colors more effectively in their creative endeavors.

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The metamerism demonstration tool

This experiment does not intend to demonstrate anything new. It is mainly aimed at explaining to color and lighting novice designers that color is not an inherent property of objects but an interpretation generated by the HSV (Human Visual System) through direct observation of the phenomenon rather than seeing it on a screen or listening an explanation from the triner. This also prevents anyone from thinking there might be a trick on the screen representation.

We carried out the experiment in a confined space on a reduced scale, allowing subjects to verify the effects visually. The project involves a black box 50cm wide, 30cm high and deep. The tool is completed with an information card explaining this optical illusion's known scientific basis. Under the box, there are two rails that house a sliding card explaining the experiment. The card is bound to the box (Fig. 2).

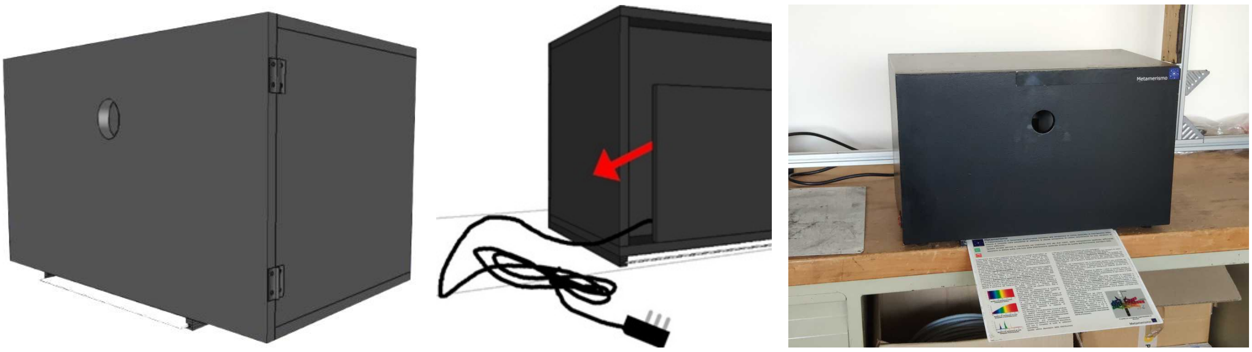

Fig. 2 - The metamerism demonstration tool.

The opening of the box has a diameter of 40mm, because the light coming from outside can interfere with the internal lighting conditions and is placed centrally with respect to the opening face on which it is positioned. For ease of transport and safety, the power cable for the electricity supply is rolled up and placed in a special compartment at the back of the box (Fig. 2).

This experiment consists of illuminating two different green color samples, first from two Luxeon Star LED source, then from a Philips fluorescent source, model TL-Mini standard 8W/33-640. When the first type of source is turned on, or under natural light, the color samples placed at the bottom appear the same to normal subjects not affected by dyschromatopsia (Dalton, 1794; Wyszecki, 1958). When the fluorescent source is turned on, however, the two color samples appear different. The internal surfaces are colored in diffusing white so that the lighting is distributed as uniformly as possible. To power the LEDs, in order to obtain enough light for the experiment, it was necessary to use a printed circuit to adjust the current from 700 to 350mA. This circuit is made up of: 1 LM 317 T integrated circuit, 2 resistors of 2W each, 1 electrolytic capacitor of 470μF – 35V, 1 polyester capacitor 220nF, 1 diode (to allow polarity inversion). The use of the integrated circuit made it necessary to use a heat sink (Fig. 3). Two switches are provided that allow subjects to turn on the LED lights and/or the fluorescent light.

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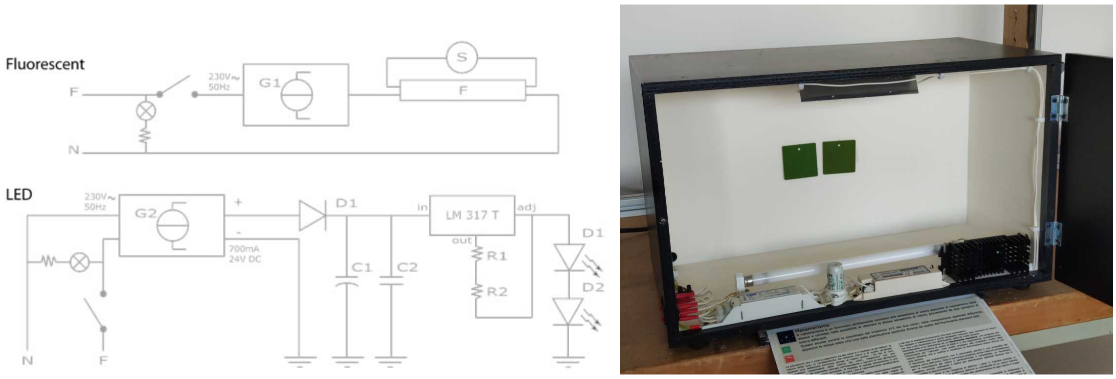

Fig. 3 - The PCB diagram an the BOX opened.

Measurement

Visual tests were conducted on 30 normally sighted subjects and confirmed the results reported in the previous paragraph. Using a Konika Minolta CL-500 spectrophotometer, the spectral irradiances emitted by the two different light sources were measured on the two color samples. On the color samples, the LED light produces a CCT=5.873K, a Ra=71 and chromatic coordinates x=0.323980898, y=0.345373303; while the FL light produces a CCT=3.929K, a Ra=86 x=0.385200351, y=0.384278387. The other chromatic and spectral data are reported in Fig. 4 and Fig. 5.

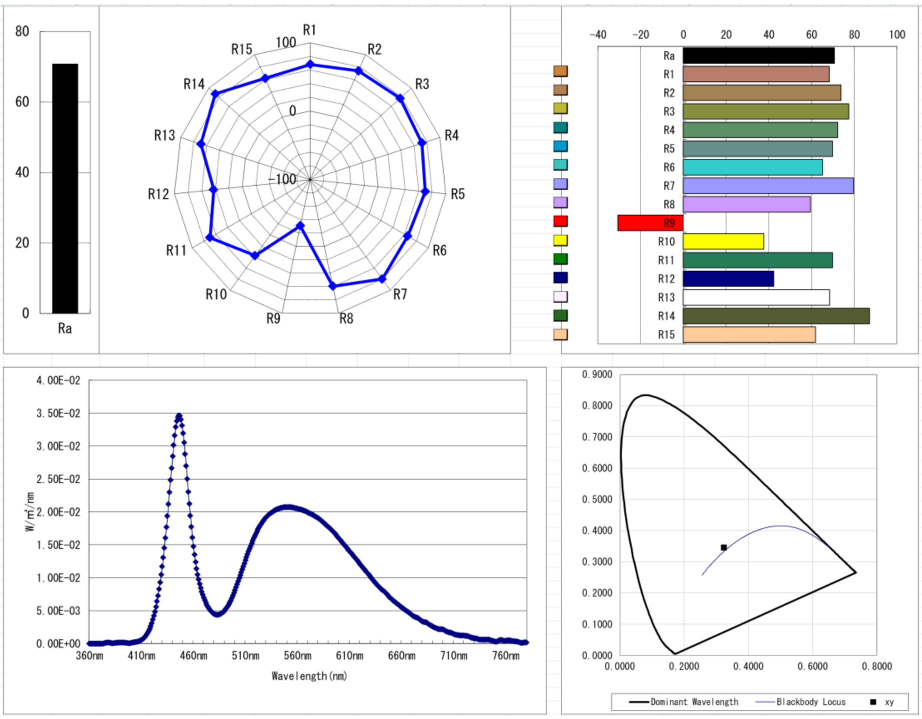

Fig. 4 – The LED.

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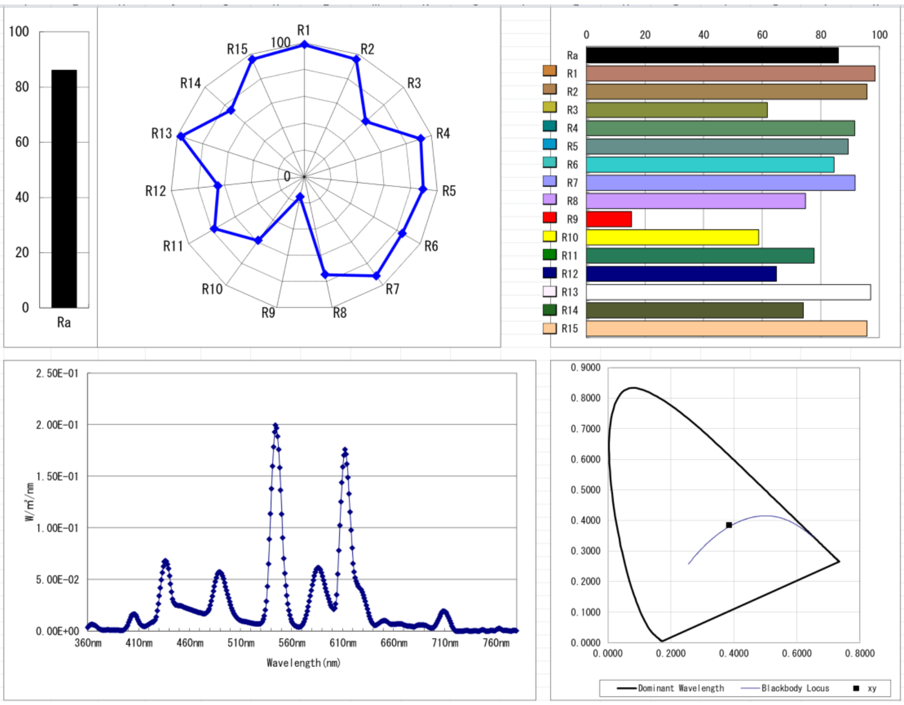

Fig. 5 – The FL.

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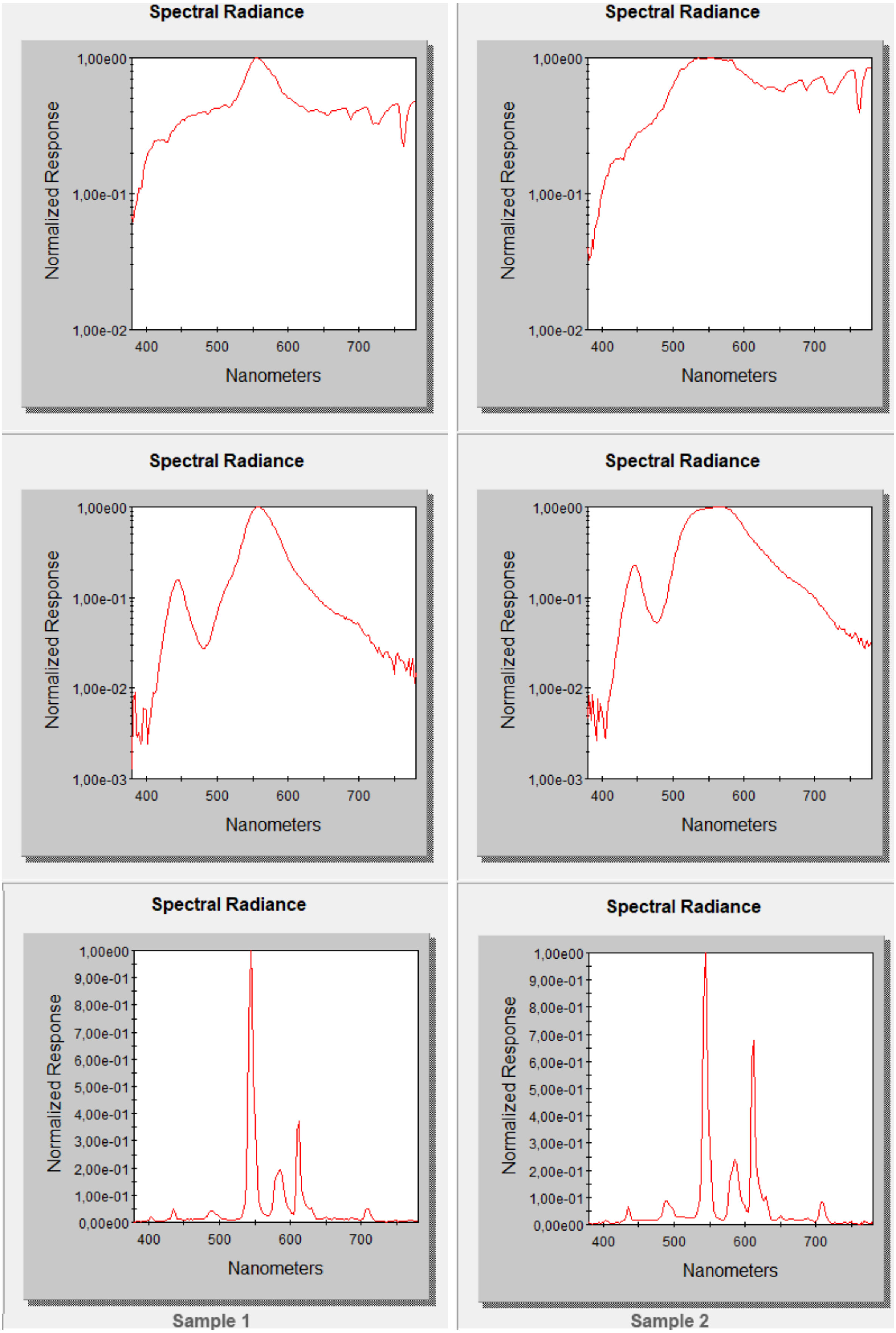

Fig. 6 - From top to bottom the two color samples illuminated by Daylight, LED light and linear fluorescent light (normalized spectrums).

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Using a Spectrascan PR-701 the spectral radiance reflected by the two color samples when illuminated by daylight, LED light and FL light was measured. All the measured data show that the spectral radiance reflected by the two color samples is always different for all three light sources, but the two samples appear the same under daylight and LED, and different only under FL light.

Discussion

We can also think of the presented experiment (as an application to color and lighting design of the experiential methodological principles created in the Bauhaus basic design. The development of Gestalt psychology, which developed in Germany at the beginning of the 20th century, significantly impacted basic design, connecting perception with phenomenological experience (Koffka, 1935). According to (Kanizsa, 1997), the experiment's goal is to establish cause-and-effect links rather than to demonstrate some weird phenomenon, and he emphasizes the importance of the method and the purpose of experimental phenomenology. This is the crucial point for the design practice. The classic experiential phenomenology method is applied to make subjects understand the importance of the psycho-perceptive aspects of colors.

The experiment has been successfully integrated into both the foundational lighting engineering curriculum and advanced courses within the Master's in Lighting Design program. It serves as a valuable pedagogical tool, bridging the gap between theoretical knowledge and practical application in lighting design education. The demonstration of metamerism through this hands-on experiment proved to be a captivating educational tool. Students were fascinated by the practical illustration of a concept that, while theoretically explained, had not been visually experienced in their practical training. This inductive teaching method, which emphasizes visual demonstration alongside theoretical explanation, significantly enhanced their understanding of metamerism.

Conclusions

In conclusion, this experiment using metameric colors highlights the psycho-perceptive nature of color, illustrating that color perception is not an inherent property of objects but a subjective experience constructed by the human mind. This insight is crucial for novice designers, who can use it to develop a deeper understanding of how light and context influence color perception. By learning to anticipate how colors interact with different lighting conditions and observers' unique visual systems, designers can refine their ability to create dynamic and meaningful visual compositions. Recognizing the subjective nature of color allows for a more intentional manipulation of light and materials, opening new possibilities for creative expression. Through this understanding, designers can craft visually engaging experiences that resonate with diverse audiences and push the boundaries of traditional color application.

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Colour is for Everyone: Teaching interdisciplinary colour foundations

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Abstract

Interdisciplinary learning has many benefits for students, including developing higher cognitive abilities, competency in knowledge transfer and integration, and skills in critical thinking and problem solving. Colour is a natural interdisciplinary topic, and is an integral knowledge component for many disciplines, spanning the sciences, humanities, arts and design. The Colour Literacy Project (CLP) aims to revitalize 21st century colour education with an interdisciplinary, experimental approach, and is developing and testing colour resources for teachers of all education levels. This curricular material serves as a universal foundation for everyone – not just art and design students. The CLP has identified four 'cornerstones' around which to structure it foundational knowledge framework: *Experiencing Colours, Describing Colours, Perceiving Colours* and *Working with Colours*. Sets of exercises from the four cornerstones provide students with a firm knowledge base for colour, and all the benefits of an interdisciplinary learning environment. The overarching framework of knowledge adapted by the CLP encompasses many disciplines, and sets the stage for acquiring higher order, discipline-specific knowledge. Preliminary results find that after undergoing our training, teachers and students alike are more engaged with colour in their surroundings, able to notice, identify and describe more colour variations, and able to ask deeper and more profound questions about colour and colour phenomena.

Keywords: colour education ; interdisciplinary teaching

Introduction

Colour surrounds us. It is a visual language that affects how we feel, helps us communicate, and helps us understand the world we live in. Although colour is ubiquitous, and plays a critical role in the way we shape our surroundings, colour studies are becoming increasingly rare at both schools and postsecondary institutions worldwide. While some basic coverage of colour perception occurs in middle and high school science classes, the bulk of colour-related education, from elementary through to high school, generally centers on using coloured media in art classes, particularly within the context of mixing paints and rehashing ideas from traditional colour theory (Schwarz, 2018). At many postsecondary institutions, colour-focussed courses have disappeared entirely, and colour is only covered as a sub-topic in a small number of art or design classes. For example, at OCAD University in Toronto, the Faculty of Design ran individual courses focussed on colour until 2019. Until then, 500-650 students would enrol in these colour courses each year, which were run by 11 faculty in 22 sections. In 2019, the structure of the Bachelor's degrees was changed: degree material broadened, with more choices made available for students outside of their chosen discipline. Colour then was taught to about 130 students, by four faculty in four sections. For the most part, colour is now studied as a subtopic within each discipline's core courses. For example, Graphic Design students will study colour for only a few weeks in an introductory graphic design course. Similarly in the Faculty of Art, 12 sections of a foundational colour course were offered prior to 2019. Today only one section is offered. The diminishing role of colour as a subject is not unique to OCAD University (Calvo Ivanovic, 2024).

A revitalization of colour education is therefore paramount – across all education levels. Expanding colour studies beyond art class is also essential. Many disciplines incorporate colour as an important component of their knowledge structure. A sample of these subject areas is highlighted in Figure 1. A contemporary colour education which embraces a balanced, cross-curricular approach that weaves together expertise and experiences from the arts, sciences, and humanities will both deepen and widen students' knowledge base, enhance their critical thinking skills, and expand their worldviews. Although individual disciplines may have their own particular knowledge framework, points of intersection common to all disciplines include the processes of observing, describing, documenting, experimenting, drawing conclusions, and solving problems. Both multidisciplinary (i.e. looking at colour within the context of a specific discipline) and interdisciplinary approaches (i.e. looking at points of intersection and commonalities between disciplines in order to gain new insights about colour) are valuable for colour studies.

> *"The most significant pedagogical developments in twenty-first century learning may not be just the continued specialisation of skills and knowledge, but the pedagogical developments through which educators and educational institutions organise learning and teaching in ways that fuse arts, sciences, mathematics and humanities domains through contemporary real-world curricula that enhances learning potentials, creative possibilities and adaptive growth-mindsets in learners."* (Harris and de Bruin, 2018)

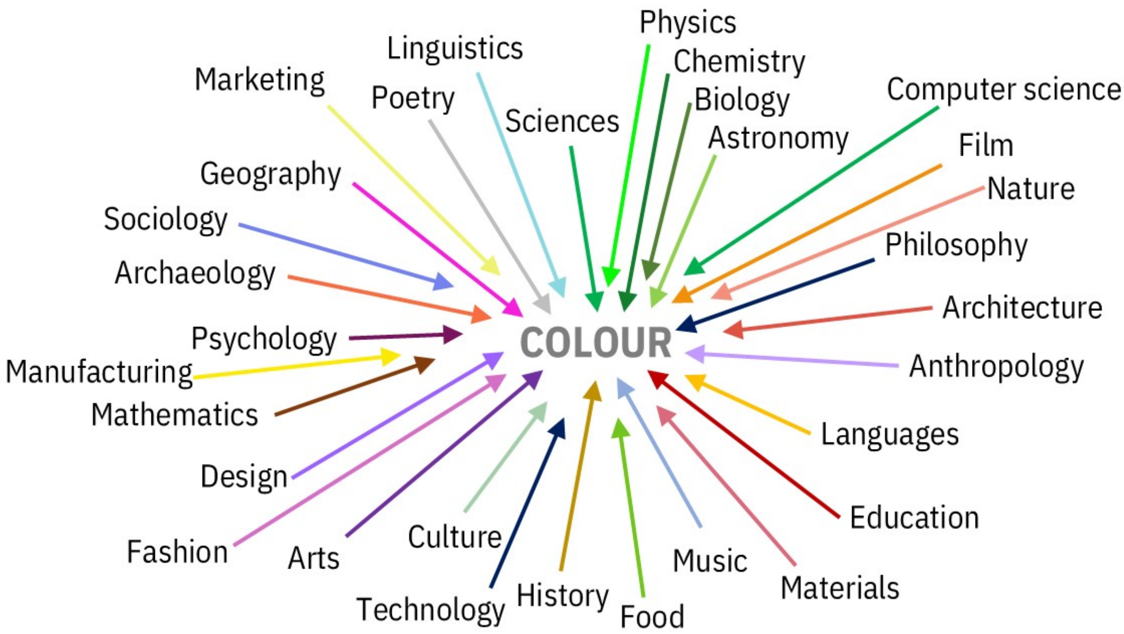

Fig. 1 – Colour lies at the intersection of many disciplines.

The Colour Literacy Project

The Colour Literacy Project (CLP) began as a response to concerns about the dismal state of colour education worldwide, following the Munsell Color Science symposium in 2018. The project aims to revitalize colour education, by providing state-of-the art resources based on peer-reviewed research for teachers at all levels – from kindergarten through to post-secondary. It formed as a joint educational initiative between the Inter-Society Colour Council (ISCC) and the International Colour Association (AIC/Association Internationale de la Couleur). Resources developed by the CLP include colour exercises, which can either be adopted as single exercises or clusters of exercises that can be easily inserted into a course to expand current content, or adopted as a large suite of exercises which comprise the backbone of a foundational, interdisciplinary colour course. Other resources include: supporting background material for teachers; handouts and lists of supplies; and a visual glossary.

The revitalized colour curriculum designed by the CLP focuses on hands-on, inquiry-based learning, putting exploration and experiences before theory and concepts.

Often, colour education starts with (and gets stuck on) the colour wheel: mixing a minimal set of ‘primary’ coloured paints to create intermediate-coloured paints. The same ideas are revisited each year, and placed within a framework of ‘facts’ about the colour wheel and colour relationships. While mixing paints can be fun, it sets up an overly restrictive view of what colour is, and ignores colour’s complexity, its contextual nature, and fails to call attention to its nuanced appearance, and the ways colour interconnects with so many parts of our lives.

By reframing colour education as a broad, multi- and interdisciplinary exploratory experience, the CLP has designed sets of exercises which are now available on the Colour Literacy Project website (2024). Testing and refining of the curricular materials are still ongoing. Three schools which have had the most extensive training in the CLP curriculum are: St. Teresa’s RCP Irlam, a primary school in Salford, England; Morristown Beard School, a middle and high school in New Jersey; and daVinci Arts Middle School, an arts-focussed middle school in Portland, Oregon. Curricular testing has grown to include a network of postsecondary institutions. Preliminary results find that after undergoing CLP training, teachers and students alike are more engaged with colour in their surroundings, able to notice, identify and describe more colour variations, and able to ask deeper and more profound questions about colour and colour phenomena.

Interdisciplinary Cornerstones

The CLP has identified four ‘cornerstones’ around which to structure a universal colour foundation for all: *Experiencing Colours, Describing Colours, Perceiving Colours* and *Working with Colours*. This foundational framework provides a fresh approach to colour education, which contains both multi- and interdisciplinary components, and is appropriate for all levels, ages, backgrounds, and disciplines of study. The foundational cornerstones are not necessarily related to single disciplines, nor do they always have clear boundaries. Elements of the arts, sciences and humanities are interwoven throughout each cornerstone, but some disciplines maybe more dominant than others within a specific cornerstone. Colour is an inherently ‘messy’ topic, and ideas and concepts associated with one cornerstone can easily flow into another. This feature is a reflection of the true interdisciplinary nature of colour. It also allows for a flexible educational approach, with multiple entrypoints for studying colour.

Building Interdisciplinarity in the Classroom: Core Colour Concepts

There is no unique place to start foundational colour studies. Rather a process which brings a series of exercises together, encompassing many disciplines and perspectives, will expand a student’s awareness of colour and its many roles in our lives. Colour is not just an exercise in art class where students mix paints. Gathering colours on a colour walk or in a colour diary, experiencing the contextual nature of colour perception in a colour illusion, noticing and describing similarities and differences between a set of coloured tiles – all constitute good places to get students engaged in colour and start to ask questions about the colours around them.

How does ‘*Experiencing colours*’ embody foundational colour knowledge? The core colour concepts in this cornerstone include:

1. We are surrounded by colours.
2. Colours play many essential roles in our lives.

Many people take colour for granted, and fail to recognize the important roles it plays in our lives. The *Experiencing colours* cornerstone contains exercises which highlight the roles that colour plays in: shaping our environment; giving us information about our surroundings; giving us points of connection to our culture; and helping us understand the complex ways that we relate to and respond to colours both on a personal level, and with a wider sociological view.

Suggested foundational activities for *Experiencing colours* include: keeping a colour diary for a day, a week, a month or longer; going on a scavenger hunt to collect or photograph a set of colours in your surroundings; brainstorming a list of the various roles that colour plays in our lives. Each of these exercises easily expands to other themes, such as documenting colour choices for the clothes we wear, or the foods we eat. Bringing attention to the wide variety of colours in our environment, and the many roles colour plays in our lives, is an important step in moving away from taking colour for granted, and moving towards purposefully engaging with it in a meaningful way, to enhance and enrich our lives. Recognizing that we are surrounded by colours, and we respond to and engage with colours every day, is a good entryway into the study of colour.

By first cultivating an awareness of all the variations and nuances of colours in our surroundings, we become more attuned to colours and can be attentive to any changes in our environment, or how new environments may differ from our usual space or place. With this foundation, through colour, we can build an awareness of the roles that our cultures, our histories and our geographies all play in shaping the world around us.

How does '*Describing colours*' embody foundational colour knowledge? The core colour concepts in this cornerstone include:

3. Colours are more than just hue.
4. Colours organization is 3-dimensional.

Expanding how we talk about and describe colours is an essential component of foundational colour knowledge. By building a broad colour vocabulary, students enhance their connections with their local environment, and gain confidence in their ability to describe their surroundings. Too often colour studies focus on naming colours with only their hues. A common misconception (and a sloppy use of language) is using 'colour' and 'hue' as synonymous terms. Instead, CLP exercises introduce the term 'Character', to describe simple variations of a given hue – i.e. vivid, muted, pale and dark. This term has been readily adopted by all who have tested the curriculum and is easily understood even by young children. The term brings an immediate awareness of the richness of colour in our environment. Characters of a given hue comprise a 'Hue family', and sets of Hue families readily lead into the 3-dimensional nature of colour organization. By starting with 3D colour models rather than 2D colour wheels, students immediately grasp relationships between colours, and can recognize and describe a wide variety of colour experiences.

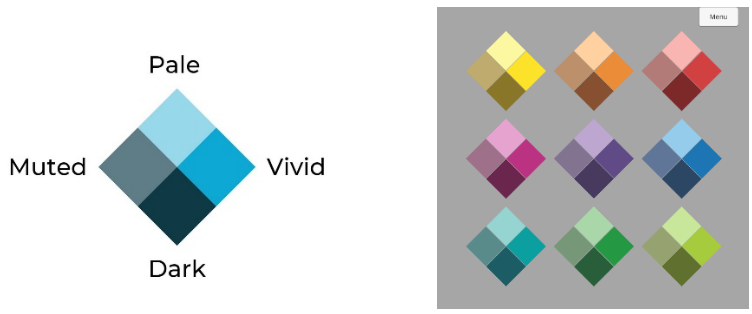

Fig. 2 – Colour characters: vivid, muted, pale and dark (left).

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Nine hue families, from the online CHROMO sorting set (right).

To introduce the foundational concepts of Character and Hue family, and to start building a colour vocabulary, sets of coloured tiles can be used to perform sorting exercises. The exercises are fun and engaging, and provide a more expansive entryway into describing and arranging colours than mixing a limited set of three paints. The CLP in collaboration with J. Sipos, has developed an online sorting tool, called CHROMO (Sipos, 2022), and also has developed handouts for physical sets of coloured tiles which can be printed. The sorting sets contain nine hue families, with four characters each, plus nine achromatic tiles. (See Green-Armytage & Maggio, 2021, for the precise colours used and motivation behind colour choices for the sorting set.)

The first exercise can be a 'free sort' where students arrange coloured tiles in any way that suits them, without using any pre-existing knowledge framework. From there, sorting exercises include chromatic vs. achromatic sort; hue family sort; and Character sort. This foundational cluster of sorting exercises builds students' vocabularies and descriptive abilities, and helps them recognize colours' three attributes or dimensions at an early stage. Hue families are readily assembled as 3D organizational models, which immediately expand descriptive abilities for colours beyond hue. Figure 3 presents two of the 3D models designed by Maggie Maggio for the CLP.

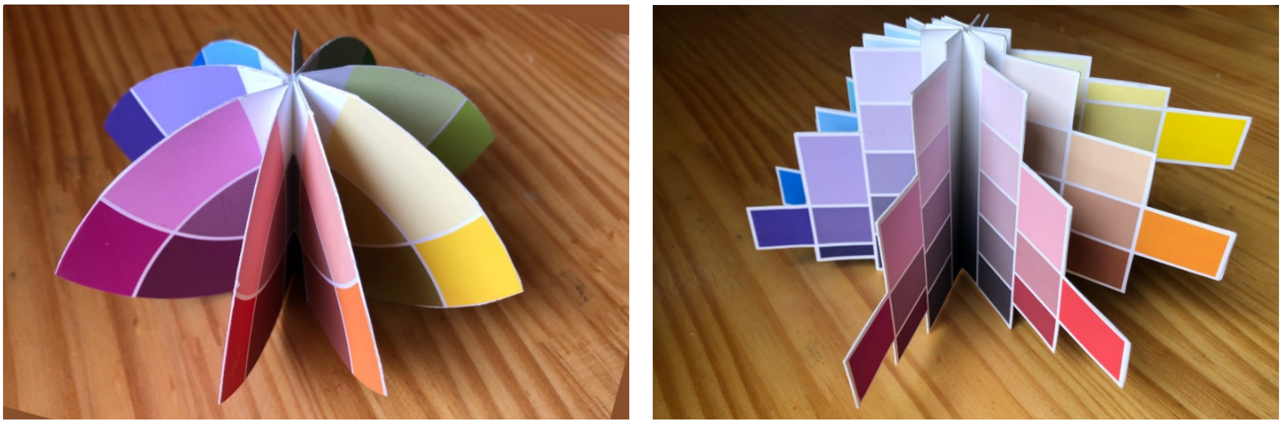

Fig. 3 – 3D Colour Models designed by Maggie Maggio for the CLP.
Hue planes model (left); Lightness-chroma model (right). Images courtesy of Maggie Maggio.

After engaging with exercises from the CLP curriculum, students from St. Teresa's RCP not only increased their vocabulary for describing colours in their environment, they also improved their facility for describing other aspects of their surroundings. With that, they gained confidence in encountering new situations, as the techniques used for describing colours were transferrable to other contexts. Colour training 'spilled over' into other subject areas and enhanced other parts of the curriculum. A poem by a Year 6 student (11 years old), would not have been written without first experiencing the CLP exercises:

> '*The muted stones sat, waiting for someone to notice them.*'

A foundation in describing colours builds vocabulary, and enhances language development as well as visual acuity. That foundation is key for many disciplines, including those within the arts and design, as well as cultural studies, sociology, marketing, languages, linguistics, and poetry.

How does '*Perceiving colours*' embody foundational colour knowledge? The core colour concepts in this cornerstone include:

5. Light is key for colour.
6. Colour perception is contextual.
7. Not everyone perceives colours in the same way.
8. Colours have a myriad of hues.

Although colour perception is an extremely complex topic, the foundational aspects of noticing and describing what you see, and noticing and describing how various contexts influence what you see can be done by even young children. Colour is a perceptual experience, and is influenced by many factors. Awareness of these factors is a critical component of a colour foundation. Also, as not everyone perceives colours the same way, an awareness of colour vision deficiencies (or *limited colour vision*) and synesthesia additionally comprise important foundational knowledge for both teachers and students alike.

Emphasizing the important role that light plays for colour can be as simple as turning the lights off. Students immediately notice that colours are much harder to see, and that their vividness is markedly diminished (when there is only a small amount of ambient light in the room). A light source can slowly be turned on to reveal the colours. Students can be asked – which colours do you see first? – to bring a high degree of awareness to their colour experiences. Noticing and describing how the amount and direction of an illuminating source impacts the colours we see can be done as another exercise, where students build a 3D cube from a solid-coloured sheet of paper, and observe the variations in the colours perceived from the different sides of the 3D cube. Students, including young children, can use colour Characters to describe what they see. Another good introductory exercise, which demonstrates how light is key for colour, is photographing the same outside location at multiple times a day, documenting how changes in the lighting impact the colours of a scene.

An alternative entryway into *Perceiving colours* is via colour illusions. These are instantaneously engaging, and immediately highlight the contextual nature of colour perception. Even though illusions may be difficult to explain and understand, their perceptual effects can easily be seen and described. The Koffka ring, Munker-White illusion and simultaneous contrast all demonstrate contextual colour experiences, and are straightforward to do. Separating the two sides of the Koffka ring instantly provokes a 'wow' factor which piques students' interest about colour. In the Munker-White illusion and simultaneous contrast, students use the same coloured crayon to colour areas which then appear as distinct. The paradox is immediately compelling, and again piques students' interest in colour, making them want to learn more.

A final possible entryway for the *Perceiving colours* cornerstone is to carefully examine an image of a spectrum. Students can be asked – how many colours (or hues) can you see? Can you give names to the colours? A common misconception is that there are only seven colours present in the spectrum – 'ROYGBIV' – made famous by the work of Sir Isaac Newton. Many introductory books about colour for children only list these seven colours, and they represent one of the few long-term pieces of information about colour that is retained by the general public, along with mixing red, yellow and blue- coloured paints. It is therefore instructive to do a close examination of a spectrum, to reveal that many, many hues are present. (In fact, Newton himself commented that the number of divisions in the spectrum was 'indeterminate'.) In this exercise, students can also be asked – which colours are *not* present in the spectrum? This question can then lead to discussions on colour Characters, achromatic colours and non-spectral colours, thus widening students' perspectives of what colour is, at the beginning stages of their colour studies.

The *Perceiving colours* cornerstone is strongly grounded in various scientific disciplines, such as biology, physiology and neurology. Building upon these introductory perception exercises, to gain a deeper understanding of how we perceive colours is an important facet of colour education for all

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disciplines. Colour perception also connects to a variety of other disciplines – like cultural studies, philosophy, languages, and history. Our memories, expectations, past experiences, language and culture all play a role in colour perception. Thus, for this topic to be fully understood, an over-arching interdisciplinary framework is necessary.

How does '*Working with colours'* embody foundational colour knowledge? The core colour concepts in this cornerstone include:

9. Colours communicate.
10. Mixing results depend on process.

A good place to start *Working with colours* is to brainstorm ways in which colours can be used to communicate – emphasizing that we do not only communicate using the most vivid hues, rather all colour Characters are necessary. Using colours to communicate draws upon both our personal associations and meanings for colours as well as our broader cultural influences and associations. Using colour as a language for communication is foundational, and by its nature, interdisciplinary.

Mixing is of course a foundational component of colour studies, but it is often done without first building a language for describing colours, or developing an awareness of all the variations, nuances, and contexts which affect the colours we see. In this instance, students may fail to recognize many fundamental qualities about colour, and how it connects to diverse aspects of our lives. The CLP saves exercises concerning mixing for the *end* of foundational colour exploration, and proposes undertaking a comparative process which explores mixing colorants using different methods and media as the preferred approach. Blue and yellow (colorants) do not always make green! By juxtaposing the subtractive mixing of paints with the optical mixing of spinning disks, and the additive mixing of coloured light sources, students gain a truly comprehensive understanding of how colorants function within different mixing processes and applications.

Building on Interdisciplinary Foundations

Once a universal foundation for colour literacy is established, further exercises within each cornerstone can then be explored, to strengthen colour knowledge. Any discipline will benefit from having students set with a basic vocabulary to describe colours, be cognizant of the contextual nature of colour perception, and be engaged with and excited about colour, because they recognize and appreciate its connection to their daily lives. Subsequent exercises gathered under the four cornerstones give students wide-ranging, interdisciplinary insights into colour and colour phenomena, from which discipline-specific knowledge can later be built.

In a first-year undergraduate Natural Science course at York University, called *Understanding Colour*, students explore colour and chemistry with hands-on 'kitchen science' experiments that include exploring dyes. Students use natural or store-bought dyes to investigate how the chemistry of dyeing works. They practise dyeing small squares of fabric at different temperatures, with and without mordants, acids, and salt, and use the scientific method write up their experiment. They are presented with critical thinking questions to further reflect on their experiment, and asked to write a short research paper on the underlying chemistry of the dyeing process, where they discuss their research in the context of their own experimental results. When students can notice and describe sometimes subtle and nuanced variations of colours they see in their experiment, they feel more confident in their results. With the CLP universal colour foundation, they understand the visual effects of looking at their fabric swatches under different sources of light, or on a coloured tablecloth. A significant learning experience occurs, as students have a compreshensive grasp of their visual experience, and the language to describe it.

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Benefits of Interdisciplinary Learning

There are several important benefits for students in interdisciplinary learning environments, which include:

1. Knowledge integration: Students develop a knowledge base which synthesizes different types of information from different disciplines, and they become open to different ways of knowing. Students recognize the benefits of connecting perspectives and techniques from multiple disciplines to provide a more fulsome picture of colour (which they then can apply to any other topic of study).
2. Achieving higher levels of structural knowledge: Interdisciplinary learning environments actively foster the development of structural knowledge, which is an understanding of higher-order relationships and organizing principles, and is associated with improved problem-solving and knowledge transfer skills and increased memory, retention, and comprehension of information learned (Ivanitskaya et al, 2002).
3. Broadens perspectives: The Science Education Resource Center (2010) describes how in interdisciplinary learning, students gain the abilities to: recognize bias, think critically, tolerate ambiguity, and acknowledge and appreciate ethical concerns.

Conclusions

A universal colour foundation structured around the cornerstones of *Experiencing Colours, Describing Colours, Perceiving Colours* and *Working with Colours* provides students with a firm knowledge base, and all the benefits of an interdisciplinary learning environment. The overarching framework of knowledge adapted by the CLP encompasses many disciplines, and sets the stage for acquiring higher order, discipline-specific knowledge. Students are enthusiastic, eager to engage in this comprehensive approach, and learn about colour.

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Color and Lighting, Color and Physiology, Color and Psychology

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The use of color in open-plan office partitions: The effect on workers' circadian response

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Abstract

This study adopts a simulation-based approach to deepen how the chromatic characteristics of partitions typically used for office applications influence workers' circadian responses, evaluated in terms of melanopic equivalent daylight illuminance (mel-EDI). Previous studies have investigated how colored walls contribute to determining the eye level spectral irradiance which, in turn, defines occupants' circadian response. On the contrary, the impact of colored furniture is still underexplored even if strongly colored elements are frequently used for office furnishing equipment. Moreover, these elements are often close to workers' eyes and occupy a large part of the field of view, hence their chromatic attributes can affect the eye level spectral irradiance more than the walls' ones. To deepen this topic, 144 different office arrangements are obtained by combining two partition layouts (low-privacy and high-privacy), three light sources' photometries (direct, indirect, and mixed), three CCTs (3000 K, 4000 K, and 6000 K), and eight partitions' colors (nuances of yellow, blue, purple, and green, each selected with 50% and 80% total photopic reflectance). ALFA software is used to perform spectral lighting simulations from which mel-EDI values are obtained. Results indicate that the impact of color choice on circadian effects may be crucial. In particular, considerably lower mel-EDI values occur for nuances of yellow in comparison to values obtained with blue nuances. On the other hand, slight differences in mel-EDI values occur if nuances of blue, purple, and green are considered. Moreover, when highly reflective colors (those with 80% reflectance level in this study, irrespective of the hue) are used, the choices of luminaires' photometry and partition layout are crucial as well. Indeed, they ensure the achievement of high mel-EDIs if indirect photometry is used and large panel portions are in front of the observers' eyes.

Keywords: circadian effects, color of furniture, light-colors interaction, open-plan offices.

Introduction

As the human lifestyle has changed in the latest years, people spend most of the day in interior spaces. Hence, attention should be paid to providing proper indoor conditions that support human well-being. In this context, light takes a key role since it influences people's being through visual and circadian pathways (Vetter *et al.*, 2021). In particular, following the recommendations proposed by the International Commission on Illumination (CIE, 2019) and the WELL Building Institute (WELL Building Standard, 2024), great attention is now given to the design of spaces in which users are provided with lighting conditions ensuring their circadian entrainment. In this respect, the spectral irradiance reaching peoples' eyes is crucial. It is the sum of the radiation directly coming from the primary light sources and the one reflected by the environment. In this context, surfaces chromatic characteristics are of primary importance since they determine the quantity and spectral distribution of the reflected component of the light. The higher the reflected component, the higher the potential of surfaces' colors to affect human visual and circadian responses. In this respect, materials' visual, or photopic, reflectance (ρ_{vis}) is commonly used to define surfaces' capability to reflect the part of the incident radiation that stimulates the human visual system, i.e., the radiation included in the range

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in which the V(λ) curve is defined. In addition, the melanopic reflectance (ρ_{mel}) has been lately proposed (Sánchez-Cano *et al.*, 2019) to indicate materials' capability to reflect the part of the incident radiation that stimulates the intrinsically photosensitive retinal ganglion cells (ipRGCs) and consequently the human circadian system. This parameter is defined according to the M(λ) curve, i.e., the curve that represents the ipRGCs spectral sensitivity to light. Both ρ_{vis} and ρ_{mel} depend on the chromatic characteristics of the surfaces.

For the above-mentioned reasons, the choice of colors for indoor surfaces is a crucial step in the building design process. Previous research has deeply investigated this topic, mostly focusing on the variations of eye level spectral irradiance due to walls' colors (Bellia *et al.*, 2017). Results in literature suggest that highly reflective surfaces generally ensure that adequate circadian stimulation is achieved (Acosta *et al.*, 2019), but selective colors (yellow and blue) always cause a reduction of eye level illuminance and circadian stimulation if compared to neutral (white) colors (Hartman *et al.*, 2014, 2017). In general, both surfaces' total reflectance and spectral characteristics need to be taken into account (Bellia *et al.*, 2024).

In this context, the effect of colored furniture is still neglected despite being an aspect worthy of investigation. Indeed, light interacts with all the elements in the environment, including furniture other than walls. In addition, furniture is likely to be strongly characterized from a chromatic point of view more than walls. Moreover, furniture's chromatic characteristics could affect the eye level irradiance more than the walls' ones because they are closer to the eyes and occupy a large portion in the field of view. These last considerations are particularly true for partitions typically used to separate workstations from each other in open-plan offices.

Based on these considerations, this study adopts a simulation-based approach to examine the impact of colored partitions on light-induced circadian response. To this end, two office layouts, three light sources' photometries, three CCTs, and eight partitions' colors are combined to obtain 144 scenarios. Rhinoceros software is used to realize 3D models and spectral lighting simulations are carried out with the plug-in ALFA.

Method

This work assumes as a case study an open-plan office (14.20 m long, 10.60 m wide, and 4.00 m high) in which different workstations for individual work and coworking are located. These are separated by means of partitions typically used for office applications, arranged in two layouts characterized by different privacy levels (Fig. 1).

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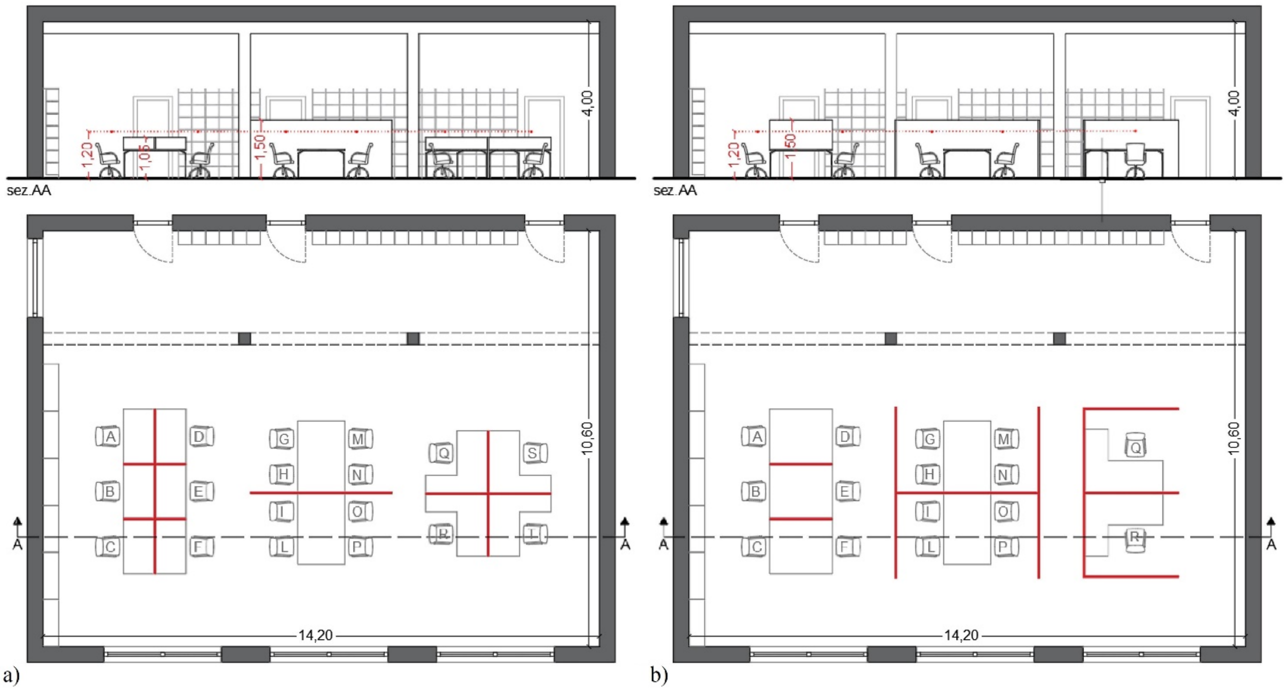

Fig. 1 – Plans and sections of the office used as a case study with the low-privacy configuration (a) and high-privacy configuration (b)

In the first configuration, spaces for individual work are separated using 30 cm high panels installed on the desks (which worktops' height is equal to 0.75 m), while partitions between the coworking spaces reach 1.50 m above the floor. It is worth underlining that 1.05 m and 1.50 m partitions are lower and higher than the observers' eye respectively. In the second configuration, all partitions are 1.50 m in height and are set up to provide workers with more privacy. For this reason, panels are arranged in a C-shaped configuration to enclose the co-working workstations G, H, M, N, and I, L, O, P, and the individual workstations Q and R. From now on, the two configurations will be indicated as low-privacy and high-privacy respectively. It can be observed that S and T workstations are missing in the high-privacy configuration if compared to the low-privacy one. Indeed, if panels 1.50 m high were used to enclose each individual workstation Q, R, S, and T, very restricted working areas would be obtained, for which to provide sufficient and uniform illuminance would be a complex issue for shading effects reason. Moreover, in these conditions workers may perceive a sense of oppression. For the same reasons, the panel that divides workstations A, B, and C from D, E, and F is missing.
Three windows are in the office, but daylight is not considered in this study. Windows are modeled only to simulate a typical office layout. Total reflectance and transmittance values equal to 10% and 90% respectively are assigned to the windows' glasses to perform simulations.
The office is alternatively equipped with luminaires characterized by three photometries: direct, indirect, and mixed (Fig. 2), each selected in three CCTs: 3000 K, 4000 K, and 6000 K (Fig. 3). For each photometry, luminaires are arranged such to provide adequate lighting conditions for office work performing according to the European Standard EN 12464-1:2021 (CEN, 2021). DIALux Evo has been used to verify the accomplishment with the Standard. Hence, for each layout, luminaires are designed to provide an average work plane illuminance equal to at least 500 lx, uniformity of illuminance higher than 0.60, and glare always lower than 19.

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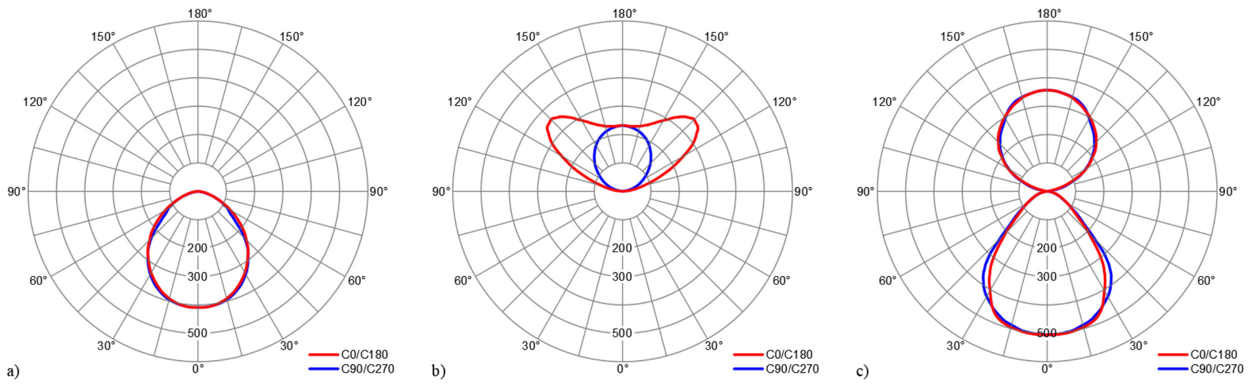

Fig. 2 – Direct a), indirect b), and mixed c) photometries adopted in the study

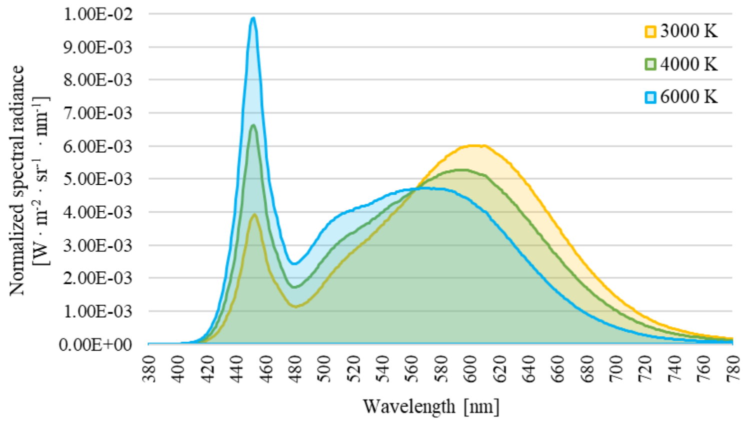

Fig. 3 – Normalized spectral radiance used in the study; each spectrum is normalized such that the total radiance is equal to 1 $W \cdot m^{-2} \cdot sr^{-1}$

Nuances of yellow, blue, purple, and green selected from the Natural Color System are alternatively assigned to the partitions. These hues are chosen based on the results of a previous study (Bellia *et al.*, 2023a) demonstrating that nuances of yellow and blue are characterized by different ratios between photopic and melanopic reflectance (i.e. photopic-to-melanopic ratio). Specifically, the ratio is the highest (higher than 1) for yellow and the lowest (lower than 1) for blue, while nuances belonging to purple and green hues show a photopic-to-melanopic ratio almost equal to 1. These findings suggest that given the same photopic reflectance, blue nuances provide higher circadian stimulation than purple and green nuances, in turn, higher than the yellow ones. In the meantime, the same illuminance levels are achieved. Hence, nuances belonging to the above-mentioned hues and characterized by almost equal total photopic reflectance values are selected among the samples available in the Natural Color System. Two reflectance levels equal to 50% and 80% are considered. A summary of the selected colors is reported in Table 1. For each color, total photopic and melanopic reflectance values are reported. It can be observed that in some cases (e.g., nuances belonging to yellow hue), for the same hue and total reflectance level, different colors are selected for the three CCTs. Indeed, it must be recalled that colors' total reflectance values depend on the light source spectral distribution; hence, the same color sample may show different total reflectance values under diverse CCTs (Bellia *et al.*, 2023b). Here, the rationale for nuances selection was to have total photopic reflectance as close as possible to each other and to 50% or 80% alternatively. Spectral reflectances of the selected color samples are measured with a Konica Minolta CM 2600-d spectrophotometer and inserted as customized materials in the ALFA library. As regards the other surfaces in the room, typical materials were selected from those already available in the library. As mentioned before, 144 scenarios are obtained by combining the two office layouts (low and high

privacy workstations), three light sources' photometries (direct, indirect, and mixed), three CCTs (3000 K, 4000 K, and 6000 K), and eight partitions' colors (nuances of yellow, blue, purple, and green, each selected with 50% and 80% total photopic reflectance). For each simulation, a calculation point is placed for each workstation at a height of 1.20 m above the floor, assuming that the person who is sitting at the desk looks straight. Hence, 18 calculation points (workstations from A to T in Fig. 1a) and 16 calculation points (workstations from A to R in Fig. 1b) are placed for simulations with the low-privacy and high-privacy configurations respectively.
As simulation's outputs, ALFA provides the spectral irradiance at the eye and the corresponding illuminance and Equivalent Melanopic Lux (EML) for the given calculation points. Mel-EDI values are derived by multiplying the obtained EML by 0.9058.

Results and discussion
Mel-EDI values resulting from simulations are reported in Fig. 4 divided into graphs according to the CCT and partition layout. Each boxplot represents all the results obtained for each simulation, i.e., all mel-EDIs calculated for workstations from A to T or from A to R for the low-privacy and high-privacy configurations respectively. In addition, Fig. 5 reports the average mel-DER values (derived from the simulated spectral irradiance) and illuminance levels for each simulation.

Table 1 Total photopic and melanopic reflectance values of the samples selected for each CCT

3000 K			4000 K			6000 K		
Sample	ρ_{ph} [%]	ρ_{mel} [%]	Sample	ρ_{ph} [%]	ρ_{mel} [%]	Sample	ρ_{ph} [%]	ρ_{mel} [%]
0585-Y30R	51.5	10.6	1060-Y30R	53.1	20.7	0570-Y30R	50.7	16.6
2005-B	53.6	56.7	2005-B	53.8	56.7	2005-B	54.2	56.8
1030-R30B	54.2	48.5	2005-R30B	54.1	53.7	2005-R30B	53.9	53.8
1030-G	53.1	56.6	2005-G	54.2	54.9	2005-G	54.5	54.7
0550-Y	76.0	41.8	0510-Y	81.8	69.4	0520-Y	81.2	61.3
0505-B	78.1	82.9	0507-B	78.5	83.0	0507-B	79.0	83.1
0510-R30B	78.1	76.2	0505-R30B	82.4	82.2	0505-R30B	82.0	82.3
0515-G	76.9	79.4	0510-G	81.1	81.0	0510-G	81.8	80.5

These data enable to better understand if the differences in mel-EDIs among the various scenarios depend on the color choice (responsible for the alteration of the spectral irradiance at the eye) or if they are mainly driven by differences in the eye level illuminance values. Indeed, being the luminaires arranged to provide always 500 lx on the work plane, different illuminance at the eye level result depending on the adopted photometry (being the eye level-to-work plane illuminance ratio determined by luminaires' photometry).
Fig. 4 shows that in the low-privacy configuration (Fig. 4a, 4b, and 4c), given a color partition, on average, similar mel-EDI values are achieved with the indirect and mixed photometries. These values are generally higher than those achieved with direct photometry.

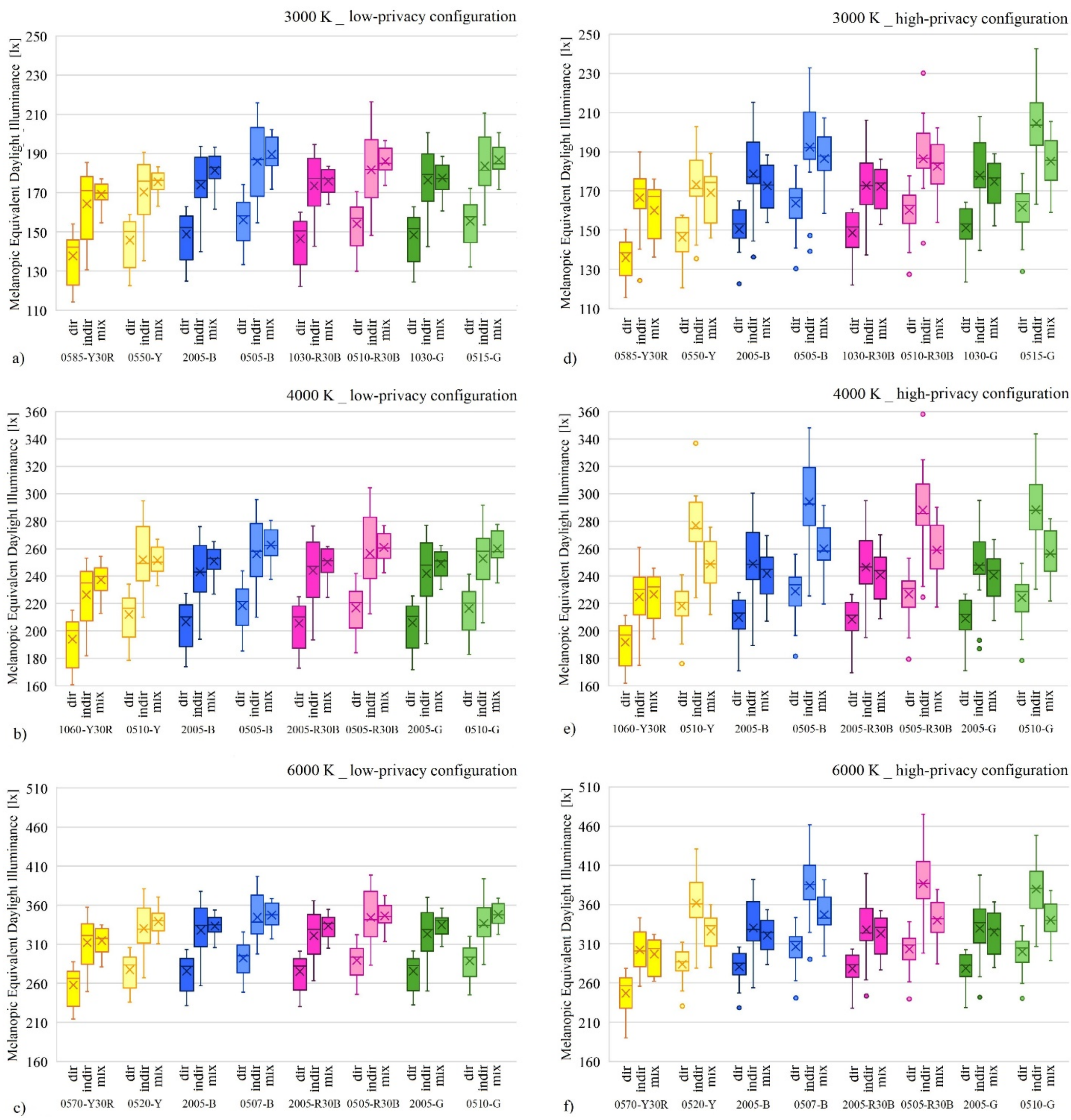

Fig. 4 – Melanopic equivalent daylight illuminance values resulting from simulations run with the low-privacy configuration at 3000 K a), 4000 K b), and 6000 K c) CCTs and high-privacy configuration at 3000 K d), 4000 K e), and 6000 K f)

In the high-privacy configuration (Fig. 4d, 4e and 4f) given a color partition, on average, the highest mel-EDI values are achieved with the indirect photometry and the lowest with the direct one. These considerations apply to all CCTs. In addition, given the color partition and the CCT, higher mel-EDI values are achieved in the high privacy configuration rather than in the low-privacy one under the indirect photometry. However, all these results are mainly due to the illuminance achieved levels. Indeed, Fig. 5 shows that given a color and CCT, similar mel-DER values are obtained irrespective of the photometry and workstation configuration (low or high), but, in the meantime, eye level illuminance strongly depends on the adopted photometry and, for a little, also on the workstations configuration.

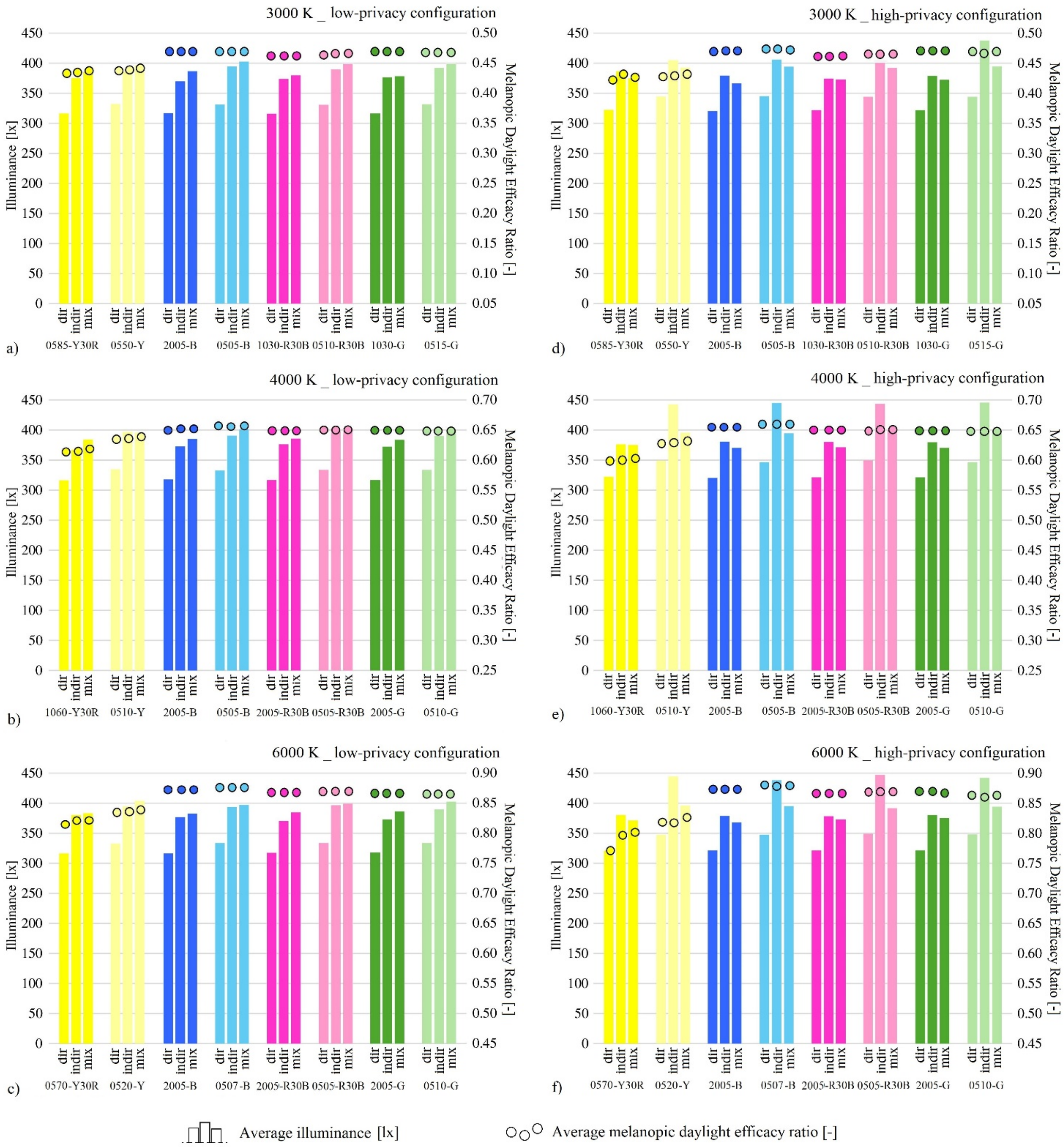

Fig. 5 – Average illuminance and melanopic daylight efficacy ratio values resulting from simulations run with the low-privacy configuration at 3000 K a), 4000 K b), and 6000 K c) CCTs and high-privacy configuration at 3000 K d), 4000 K e), and 6000 K f)

In particular, as expected, higher illuminances are achieved with the indirect and mixed photometries as compared to the direct one. The higher illuminance values registered with the indirect photometry in the high-privacy configuration can be explained considering that if compared to the case in which there are no partitions in front of people' eyes, being close to the eyes, they reflect a considerable light quantity. Indeed, this is particularly noticeable when 80% reflectance level is considered. As regards the influence of the different colors on mel-EDIs, it can be observed that, on average, the lowest values occur when nuances of yellow are used. On the contrary, similar results are generally achieved with nuances of blue, purple, and green. In particular, blue nuances generally provide the highest mel-EDI values, followed by green and purple nuances. However, the observed differences are clearly noticeable only with nuances belonging to yellow hue, while blue, purple, and green provide almost similar results. These considerations apply to all CCTs, photometries, and partition layouts. These findings were predictable based on the colors' total melanopic reflectance. In this regard, Fig. 5 shows that mel-DER values are always the lowest with yellow nuances, while blue, purple, and green provide similar values. Of course, Fig. 5 confirms that, given the photometry, partition layout, and total reflectance level, the achieved illuminance values at the eyes are equal for nuances of yellow, blue, purple, and green, they being characterized by almost equal total photopic reflectance values.

Conclusions

The choice of colors for inner surfaces is a crucial step in the building design process since the chromatic characteristics of all the elements in the environment contribute to determine light spatial and spectral distribution, and, in turn, people's circadian response. Since now, this topic has been studied mainly considering how walls' colors affect the eye level spectra irradiance, disregarding the effects that colored furniture may have as well. This study examines how colors applied to partitions typically used for office applications may influence workers' circadian response. To this aim, spectral lighting simulations are run by means of ALFA software for 144 different office arrangements obtained by combining two partition layouts (low and high privacy), three light sources' photometries (direct, indirect, and mixed), three CCTs (3000 K, 4000 K, and 6000 K), and eight partitions' colors (nuances of yellow, blue, purple, and green, each selected with 50% and 80% total photopic reflectance). Results demonstrate that the impact of color choice on circadian effects may be crucial. In particular, considerably lower mel-EDI values occur for nuances of yellow in comparison to values obtained with blue nuances. On the other hand, slight differences in mel-EDI values occur if nuances of blue, purple, and green are considered. Moreover, when highly reflective colors (those with 80% reflectance level in this study, irrespective of the hue) are used, the choices of luminaires' photometry and partition layout are crucial as well. Indeed, they ensure the achievement of high mel-EDIs if indirect photometry is used and large panel portions are in front of the observers' eyes.

Future research should be carried out to extend the results considering daylight in addition to electric light. Moreover, even if simulation-based studies allow to compare a lot of different design configurations, on-field measurements should be performed to verify the results arisen from simulations. Last, by estimating mel-EDI values, this study has illustrated the influence of colors on people's well-being only by accounting for the effect on circadian entrainment. However, it must be underlined that colors are often capable of evoking emotions and feelings which can be also related to the cultural background or previous experiences. These feelings influence people's comfort within an environment as well. Further studies are needed to investigate this aspect, by applying ad hoc procedures to investigate people's common preferences.

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Lighting and Colour profoundness, the building up of an initiatory pathway to human need of shadow

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Abstract

Lighting design is a visual decision that has many implications on our behaviour, on our brains, on our minds, our consciousness, on the way we attribute a meaning to spaces, surfaces, objects, and in a very particular way, to colours.

Sustainability, energy saving, and consciousness raising about the impact of luminous pollution on biodiversity, especially within and around urban areas, have brought back humanities' attention to the original need for low levels of illuminance and to the familiarity with shadow. Consequently, the widespread habit of systematically raising visual resolution by increasing the illumination level is now being questioned, even within urban lighting projects.

Attaining colour profoundness through lighting projects is an opportunity to chronicle the sense of shadow and obscurity in our everyday lives. Behind its very interlaced correlation with the notion of colour lightness, it opens reflections on what we have to build up to re-conquer the acceptance and the enjoyment of the indispensable shadowed atmosphere, which is fundamental for sleep preparation from the very moment of twilight. It will free the way to an initiatory individual practice of building a progressive visual approach that encourages the beholder to question his/her own individual viewing condition (Kandel, E.R., 2016).

Because it addresses a deeper aspect of our 'expectations', whether 'affective' or 'emotional',(Lam, W.M.C. 1992) the most delicate aspects of distributing luminances on colours, surfaces, and objects (which is the fundamental method for the lighting design project's visual accomplishment), is the monitoring of those infinitely extended nuances of low lightness (Leonardo). Those gradations will define the quality of what we perceive as shadow by opening a way to total darkness, toward this area where our vision transits toward our imagination.

The functional or aesthetic needs within an interior architecture, a scenography, or an outside architectural landscape will then cohabit with the feeling of some ultimate celebration of specific colours. This visual journey from darkness to nascent lightness, will enable us to explore the sensation of reaching what we might call its inner nature.

Keywords: colour, lighting, perception, visual, embodied mind, aesthetics, brain-body interactions.

Introduction

In our article *Visual studies, a new opportunity for the theoretical thinking of architectural lighting design* we have previously explored the various reasons why lighting design must be considered a fundamental visual decision, for "… it is the result of a visual architectural thinking", that provides stimuli from its spectral composition, according to a temporal pattern, all along various light levels in order to orchestrate our visual perception for functional and aesthetic reasons.

This brings us ever closer to Robert Edmond Jones lines when he wrote that ‘we use light as we use words, to elucidate ideas and emotions. Light becomes a tool, an instrument of expression, like a paint brush, or a sculptor’s chisel, or a phrase of music.’ (Jones, R.E., 1941). More technically it means that “the lighting designer distributes luminances (from luminosity to shadow), that’s to say: intensities, spectral distributions, light distribution, according to their provenance or their direction, all over the environment”, on surfaces, colours, and objects. It evokes what painters do when they apply shadow and light to their canvasses, aiming to stimulate the viewers emotions, resonating deeply within his/her mind. Although painters were among the first artists Giorgio Vasari referred to as the ‘artefici del disegno’ (Garin, E. 1990) demonstrating how their intent engaged with our fundamental visual ability to perceive low light and some of our deepest desires, recent concerns about sustainability, energy saving, light pollution, and the effects of the biological clock, have significatively prompted us to reevaluate our needs for luminance and illuminance levels.

Sustainability, energy saving, and light pollution on the way to shadow experience

It’s clear that reducing lighting levels and controlling lighting distribution have visible effects on energy saving and light pollution, principles now supported by EU institutions. In some cases this focus has led, by correlation, to lower lighting levels and, due to growing concerns about biodiversity, to a reflection on the correlated colour temperature (CCT) that indirectly brought effects on the spectral power distribution.

According to the 2022 report “Light pollution reduction measures in Europe” published during the Czech Presidency of the EU Council, some countries like Croatia, France, and Slovenia, have enacted laws and measures specifically addressing the causes of light pollution. These regulations even provide guidance on correlated colour temperature (CCT) (Ministry of the environment of the Czech Republic, 2022).

In France, for example, the rules developed through institutional processes have indirectly influenced lighting design practices. While they focus on light pollution and biodiversity, they also have a correlated impact on human wellbeing, integrating these concerns into everyday practice. Those happened to be a sustain to the collaborative approach lighting designers had previously developed in the past years as an educational monitoring of community needs, which had aligned with key requirements for addressing light pollution and biodiversity. Consequently this alignment has also met essential requirements for human well-being at night, such as appropriate lighting levels and spectral colour distribution.

These initiatives have been elaborated in order to stimulate reflections among citizens, through nocturnal walks led by lighting designers, occasionally with the participation of sociologists or psychologists. In such conditions these walks offer an opportunity for a closer analysis of the common belief that raising the lighting level brings more security. Such experiences provide individuals with the vocabulary to explore and express their feelings about the negative effects of excessive glare from harsh lighting. This in turn has reinforced the authority of lighting designers in promoting well-being and responsible lighting practices.

In this context, external lighting projects become foundational. They allow lighting designers to engage with user’s insights, helping them create visual environments that balance both functional and aesthetic lighting choices, using carefully considered gradients of light.

Let’s explore other situations where a careful analysis of light gradients enhances visual comfort and aesthetics both indoors and outdoors. These situations include:

-Decorative purposes: this can be found in both professional and private settings, often to maintain a nighttime atmosphere and support the biological clock repositioning principle.

-Commercial purposes: in specific retail spaces, especially those selling luxury or artistical products, thoughtful marketing eventually leads to the use of a very delicate lighting instead of the more common trend to bring more and more brightness.

- Exhibitive lighting principles: here a full range of light gradients is used, from the darkest shades to brighter areas. This creates a dynamic interaction between observation and contemplation. Shadow around the lighted exhibit prepares our gaze and our mind to isolate it out of its background, out of our temporary distraction or indifference, it stimulates our sensitivity and our vulnerability. It help focus our attention, bringing us closer to the exhibition purpose while also opening a way to our sensitivity, to our vulnerability. According to the gradation of contrasts, this can either lead to an experience of "visual extraction" within the exhibition or integrate the exhibit into a broader atmosphere of thought with the creation a whole "visual bath".

-Supporting biological clock repositioning: lighting designers create environments that cater to the user's nighttime needs for intimacy, enhancing the enjoyment of the night. By focusing on colour absorption rather than reflection, they set the stage for the body's natural cues to prepare asleep at the right time of the evening.[2]

Within the technical and legal framework of lighting design, one of the designer's key responsibilities is to highlight the behavioural and emotional dimension of lighting. This involves understanding how lighting affects our perceptual and aesthetic experience, which significantly influences how we enjoy the architecture.

From what William MC Lam, calls 'the attributive stage of perception' or the 'attributive classification of visual stimuli', we will anticipate our moving through the architecture. From the 'affective components of perception' and from the 'attributive classification of visual stimuli', we will assign a functional, a cultural, or an emotional 'meaning' to a room, an object or a volume we are headed to. Our accumulated visual information ultimately determines for which purpose and how to spend time for functional or emotional reasons interacting more or less intimately with those specific areas of the architecture[3].

In this context, the goal of lighting design is to align with what William MC Lam defines as the viewer's 'expectations' which are 'interwoven' with their 'attributive', and 'affective' responses[4]. Alternatively, designers might choose to take a "step aside" from these expectations, embracing an artistic approach that surprises and engages the viewer. This approach will lead us toward what Kandinsky called our 'inner resonance' Kandinsky W. (1946), or what Ludovico Dolce described as what '…the painters and the poets represent from the nature', that's to say 'all what is demonstrated to the eye (…) as much as what is represented to the spirit' Dolce L. (1622). This intentional "step aside" aims to create an element of surprise and wonder, fostering the emotional aesthetic experience.

Transition to darkness, vision, and to the creative mind

From the experiences we have encountered and documented over time, we've determined that the feeling of profoundness—both as sensation and idea—depends on insights that Alexandre Melay

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[3] Caratti-Zarytkiewicz Lighting Design: The Result of a Visual and Non-Visual Architectural Reflection
[4] Lam W. MC. p.34

points out in quoting Georges Didi-Huberman's "L'homme qui marchait dans la couleur". Didi-Huberman highlights the contemporary artist's interest in uncertainty, defining it as a rejection of 'the distinction between the correct vision and the illusory one, between what is true and what is false. He describes his exploration as the creation of fairy tales, spaces where dream and reality blend' (Melay A. 2022). It also reminds Giovanni Paolo Lomazzo's observation when he described the colour that in a first step before it is illuminated 'is visible only in potentiality' and then in a second step 'by the benefit of the light [it] may be actually seen' (Tramelli B. 2017).

Commonly this research, when it regards colour, begins with the concept of lightness on the Munsell scale, which connects us intuitively to how we perceive more or less lighting on colours. Ultimately, we experience true depth when we feel a real sensation of ambiguity, communicated by darkness. As we approach this darkness, we explore the limits of our vision within an aesthetic context, prompting us to develop coordinated scenographic and lighting strategies, that will enshroud the architecture by generating feelings of profoundness.

By using shadow, we aim to evoke a sensitive hypothesis of 'Tenebrae', hinting at the existence of an unknown frontier surrounding us. To achieve this, we will leverage the capabilities of our far peripheral vision—specifically the 30 to100/110° from our central vision axis. Here our clear perception of shapes begins to fade, leaving us only with a sense of colour, and at the edges of our visual field, we are stimulated only by movement.

As we subtly scan our environment, we draw closer and closer to the encroaching darkness around us. The diminishing luminance surrounding the central field (where visual extraction to a specific area of the brain occurs [Zeki S. 1999]), creates a shaded contrast between what can be examined in detail through our foveal vision and the progressive sense of something beyond, perceived only through our peripheral vision (Fig.5). This interplay flirts with the boundary between the tangible and the imaginary, creating a continuous tension between clarity and the unknown.

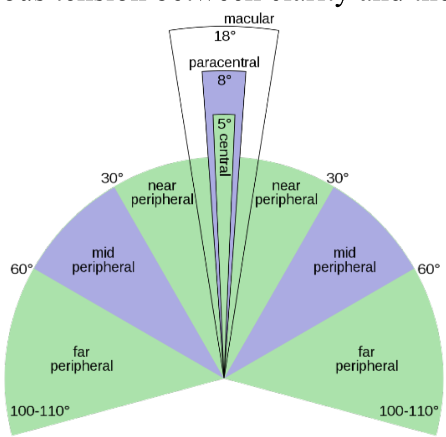

Fig.5 Peripheral vision By Zyxwv99 - Own work, CC BY-SA 4.0, https://commons.wikimedia.orgwindex.phpcurid=37052186.svg

Profoundness as an 'inner resonance'

The concept of profoundness is central to our understanding. Rather than focussing solely on technical definitions, it's essential to reflect on our shared human experiences, which are shaped by a variety of socio-cultural influences, visual perceptions and emotions.

According to the 2024 Merriam-Webster dictionary 'profound' suggests 'intellectual depth and insight, difficulty to fathom or understand' descending 'far below the surface', within 'the depths of the sea'. The 1953 American College dictionary directly alludes to what is 'penetrating or entering deeply into subjects of thought or knowledge', linking to the notion of what is 'intense' and 'extreme', to what has a 'deep meaning'. The 2024 Webster's Writer's Dictionary introduces the term 'overmastering' which suggests, for those who attain profoundness—whether through intellect or skill—experience a significant achievement. References to the sea and the act of diving further, of being engulfed, underline this idea.

However, we find that the concept of profoundness also extends to the celestial realm, where the infinite sky evokes a different sense of space. This feeling can arise under a bright blue sky, or under the vastness of a starry night. Kandinsky articulated this emotion powerfully, suggesting that 'the deeper the blue, the more it beckons into the infinite, arousing a longing of purity and the super sensuous'. He described this blue as 'the colour of the heavens just as we imagine it when we hear the word heaven' (Kandinsky W. 1946).

The search for profoundness invites us to confront uncertainty, where we may feel an oscillation between the fear of losing of ourselves and the meditative state that connects us to mysterious and unsuspected questionings and insights. Profoundness encompasses both these experiences in a similar way to Tenebrae, which can conjure fear or meditation. Ultimately, it is the artistic discourse that allows us to choose between these paths. This exploration stimulates our imagination, drawing us toward realms that are difficult to articulate—areas akin to those explored in psychoanalysis, where the unconscious resides.

Profoundness of colour seen through two architectural lighting experiences.

- Exhibition *Azzedine Alaia, Couturier Collectionneur*, Musée Galliera in Paris (2023/2024) scenography Studio Matters, lighting design Alexis Coussement (ACL).

The visual experience created by ACL in this exhibition involved a delicate interplay between reflectance and absorption. This constant alternation allowed viewers to engage deeply with the important visual decision that transform a piece of clothing into an object of contemplation.

Exhibition *Azzedine Alaïa couturier collectionneur*, Musée Galliera, Paris 2024, Photo Alexis Coussement

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The low lighting levels used throughout the exhibit maintain a sense of mysterious questioning around darker, absorbent colours, such as brown, dark blue, and dark green. These colours contrast with reflective ones, which stand out because they reflect light more effectively. When both types of colours receive the same quantity and quality of lighting, the reflective colours become more visible due to their shine. This approach establishes two distinct visual principles from one single lighting: on one hand, the striking impact of reflective colours, and on the other, the more internalized perception of absorbent colours, especially when they fade into deep darkness.

-Paolo Roversi exhibition in the Musée Galliera in Paris 2024, scenography Anya Martchenko, lighting design Akari-Lisa Ishii (ICON).

This project is built on a combination of liminal messages aimed at communicating through the scenography how deeply Paolo Roversi's works penetrate the beholder's mind. His art, characterised by abstract stimuli and a unique visual philosophy of the undefinition of the final meaning, paradoxically positions itself as a shrine to luxury products while ultimately reaching the visitor's soul.

Surrounding this unexpected visual/artistic message, Ania Martchenko and Akari-Lisa Ishii have created a perspective that mysteriously bridges our central and our peripheral vision. This perspective relies on a carefully distributed lighting scheme that begins with the artwork itself, the picture, and then find a constant continuity with the inner image of the architecture the viewer will then build up on his own.

As we move outward, this lighting gradually dims, interacting with the red painted walls and contributing to a shrine-like atmosphere. The design creates a subliminal visual pathway from the depths of the hall's darkness, allowing each artwork to quietly enter our visual field. This process guides our understanding into the realm of the imaginary, potentially engaging our brain's creative faculties.

Paolo Roversi exhibition in the Musée Galliera in Paris 2024

Linda Kristiansen's theatrical, photographic vision

Halfway between architectural and theatrical vision, we encounter Linda Kristiansen's photographic work, *Stillness of Heart*. Within this picture, the peripheral area emphasises depth and contemplation, even embracing total darkness. Here Tenebrae contributes to the atmospheric quality, while its essence is also reflected in the water, where colours and shapes become indistinct.The atmosphere evokes memories of Rome's Palazzo Barberini Narcissus, a painting originally attributed to

Caravaggio by Roberto Longhi, but also to Giovanni Antonio Galli, known as Spadarini, according to experts like Gianni Papi and Mina Gregori (Finestre sull'arte 2013). In this photo, Linda Kristiansen incorporates a red fabric, like a reminiscence of Caravaggio's use of similar elements in his works. Over this fabric is delicately laid down a very low lighting level, allowing its folds to express deep darkness while also revealing a mysterious vibrancy when the light mysteriously interacts with the colour.

This interplay prepares our minds for the inscrutable darkness surrounding it, guiding us toward areas where our vision becomes completely absorbed in a kind of visual silence, a dimension that could be likened to Dante's description of "a place where every light is mute" (Dante).

And if silence, for Leopardi "is the language of every powerful passion, of love (…), of wrath, of amazement, of fear" (Leopardi 2023), it also embodies the unspeakable emotions of drama, which remain an unresolved question, an abstraction destined to elude expression.

Fig. 3 Stillness of Heart Linda Kristiansen www.lindakristiansen.no

James Turrell's work on the unconscious around the limit between vision and the imaginary.
James Turrell's approach allows us to experience a deep sense of profoundness. Many of his works, such as *Breathing Light* (2013) and *Tight End* (2005), completely envelop the beholders, as they are patiently adjusting their vision. This gradual adaptation process helps visitors move beyond an initial feeling of harmonious disorientation. This the result of an intent. Turrell describes this intention with the following words: 'My work has no object, no image and no focus. With no object, no image and no focus, what are you looking at? You are looking at you looking. What is important to me is to create an experience of wordless thought', says James Turrell. (Kandel E.R. 2016), This approach resonates with the neuroscientist Eric Richard Kandel's comment, a 2000 Nobel Prize winner in medicine, who notes: 'Turrell's installations allow viewers to explore light, colour and space. They bypass our conscious mind and access and celebrate the optical and emotional effects of luminosity on our unconscious." (Kandel E.R. 2016)

Conclusion
To conclude we will introduce an important scientific perspective on the idea of profoundness. A 2012 study by Umiltà et al at the University of Parma based on the observation of a "spatialist" painting by Lucio Fontana, known for its knife cuts. The study found that viewing these cuts activated the viewer's cortical motor system differently than viewing simple lines (Umiltà 2012). This scientific insight adds depth to our reflections and feelings on the impact of shadows. In this case, the suggestion of a mysterious space behind the painting stimulates our brain's motor cortex, as if inviting us to explore its depths. This raises questions about how impressions of shadows, or the obscurity created

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by gradually darkening colours in architecture, according to an artistic strategy, influence the way we anticipate our movements within that space, as well as our creative imagination.

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RGB illuminant compensation using multispectral information

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Abstract

In the pursuit of more accurate color reproduction in digital imaging, this paper explores the integration of multispectral information to enhance RGB Automatic White Balance (AWB). Traditional AWB methods, which rely solely on RGB data, often struggle under varying lighting conditions. To address this, we investigate three approaches: i) extending RGB-based color constancy algorithms into the multispectral domain; ii) utilizing ambient sensors for real-time illuminant detection; iii) reconstructing spectral data from RGB images for subsequent spectral AWB. Our methods include advanced re-elaboration techniques to refine illuminant estimation before applying them to RGB data. Experimental results demonstrate that these multispectral approaches can significantly reduce color reproduction errors, achieving up to a 60% improvement over conventional methods. The findings suggest that integrating multispectral data into AWB algorithms offers substantial benefits for applications in photography, remote sensing, and medical imaging

Keywords: Spectral Imaging, Illuminant Estimation, Automatic White Balance

Introduction

RGB color compensation in digital imaging refers to the process of adjusting the levels of Red, Green, and Blue (RGB) in an image to correct or enhance its color balance (Gijsenij *et al.*, 2011). This process is essential because various factors, such as lighting conditions and camera sensor characteristics, can cause the colors in an image to appear inaccurate or unnatural. In professional digital photography color compensation is typically achieved through image editing software, such as Adobe Photoshop, GIMP, or Lightroom, which allows manual adjustment of RGB channels.
This can be done through levels, curves, or color balance tools. To further facilitate this task some cameras allow you to set a custom white balance by taking a reference photo of the gray card. The camera uses this information to adjust the RGB channels for the subsequent shots to ensure correct color balance. Color compensation using Automatic White Balance (AWB) is a technique used in most cameras and mobile phones to correct the color of images so that white objects appear white under different lighting conditions regardless of the color temperature of the light source in the acquired scene. This is done by automatically analyzing the image content. Once the most likely white point is determined, the image's color channels (Red, Green, and Blue) are adjusted accordingly by the algorithm. If the light source has a warm tone (e.g., incandescent light), the algorithm increases the Blue channel to counteract the yellow/red tint. If the light source is cool (e.g., fluorescent light), it increases the Red channel to counteract the blue tint. AWB compensation should ensure that the overall color balance of the image is natural, and the colors appear as they would under neutral lighting conditions, however AWB algorithms may badly fail when there are very few colors in the scene, for example a photo of a blue sky (they might misinterpret the overall color cast and adjust the colors incorrectly, leading to unnatural results), or when there are multiple light sources with different color temperatures in the same scene. For example, a room with both daylight from a window and incandescent lights can be challenging to balance.

Advancements in RGB-based Automatic White Balance (AWB) algorithms have focused on improving their accuracy, adaptability, and robustness in varying lighting conditions (Barron *et al.*,

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2017; Bianco *et al.*, 2015; Hu *et al.*, 2017). Despite these improvements, several intrinsic limitations remain due to the fundamental nature of RGB data (Buzzelli *et al.*, 2023a). To overcome these limitations, we may require integrating additional types of data, such as multispectral imaging, depth information, or more sophisticated scene understanding, to achieve more reliable and accurate white balance correction.

In this work we summarize our recent attempts to achieve RGB color constancy, focusing on three main approaches: **spectral-based** (Erba *et al.*, 2024a)**, spectral ambient sensor-based** (Erba *et al.*, 2024b)**, and based on spectral recovery from RGB data** (Agarla *et al.*, 2022; Buzzelli *et al.*, 2023b).
Spectral-based methods, as shown in Fig. 1, utilize multispectral imaging to estimate the scene illuminant more accurately across various wavelengths, which is then converted into the RGB domain for color correction.
Spectral ambient sensor-based methods, illustrated in Fig. 2, involve using external sensors to measure the scene's lighting conditions directly, which can then inform the color compensation process.
In the last approach, as shown in Fig. 3, the full spectral profile of the scene is reconstructed by a process of **spectral recovery from RGB data**. Once the spectral data is recovered, spectral-based methods are employed to estimate the scene illuminant with a greater accuracy across multiple wavelengths.

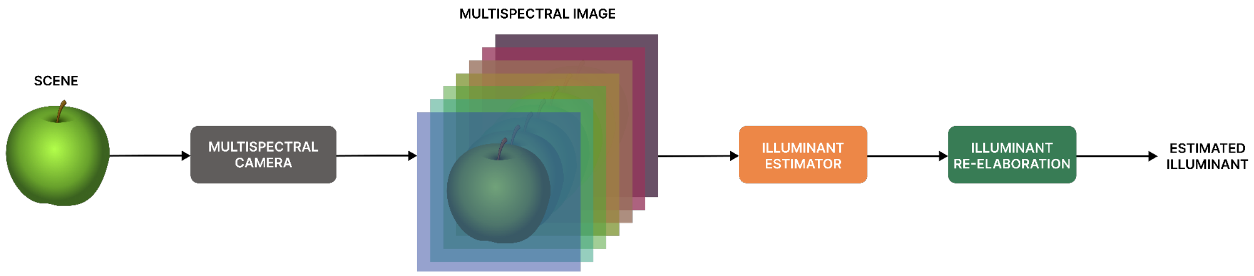

Fig. 1 - Spectral-based illuminant estimation

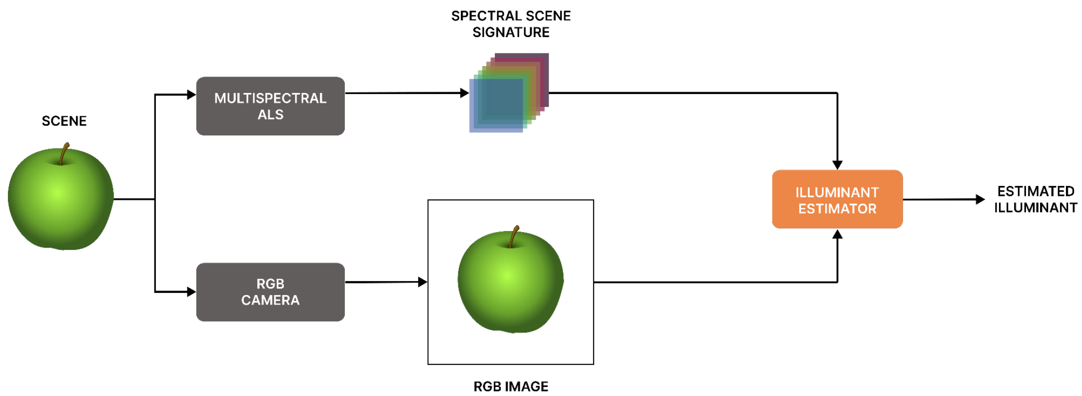

Fig. 2 - Spectral ambient sensor-based illuminant estimation

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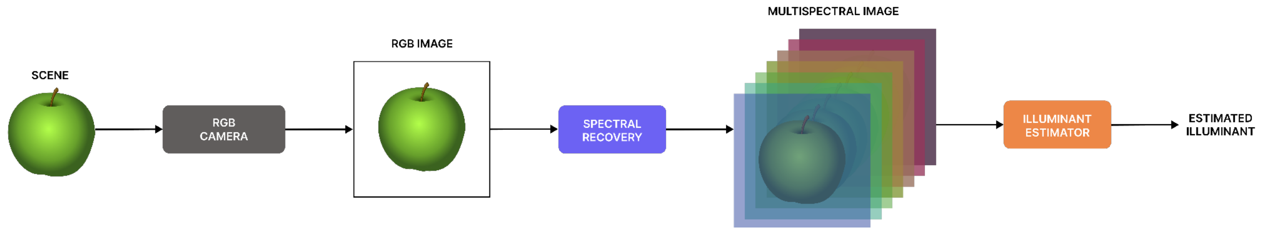

Fig. 3 - Spectral recovery-based illuminant estimation

Spectral-based Automatic White Balance

It is likely that future mobile phones will include high-resolution multispectral sensors. Traditionally used in fields like agriculture and medical imaging, multispectral technology is becoming more feasible for mainstream devices due to advancements in miniaturization, which reduces the size and cost of these sensors, making them suitable for integration into mobile phones. Considering this observation, in our paper titled "RGB Color Constancy Using Multispectral Pixel Information" (Erba *et al.*, 2024a) we propose a novel method to enhance computational color constancy by leveraging multispectral imaging for illuminant estimation and subsequent correction in the raw RGB domain. To this end, we extend a set of existing camera-independent RGB illuminant estimation algorithms to operate on multispectral data and investigate whether this richer data source can improve the accuracy of color constancy.

Our methodology involves two primary steps:

1. **Multispectral Extension of RGB Algorithms:** We first extend a selected number of sensor-independent AWB algorithms belonging to the edge-based color constancy framework (Van De Weijer *et al.*, 2007) from the RGB domain to a multispectral domain. However, we found that merely extending these algorithms to multispectral data is insufficient for achieving optimal color constancy.

2. **Re-elaboration of Multispectral Estimations:** To overcome the limitations of the initial step, we introduce a process to re-elaborate the multispectral estimations before converting them into raw RGB data. This step involves using the camera sensitivity function and various re-elaboration methods, such as average multiplicative weight, average additive bias, optimization-driven multiplicative weight, and feed-forward neural networks. These methods aim to refine the accuracy of the final RGB illuminant estimation.

Our results, validated on the NUS dataset (Nguyen *et al.*, 2014), demonstrate a significant improvement in color constancy performance, with a 60% reduction in mean reproduction angular error compared to traditional raw RGB methods.

Spectral ambient sensor-based Automatic White Balance

The motivation for this work stems from recent technological advancements in spectral imaging and color correction, as highlighted by a recent patent from Apple (Jia *et al.*, 2020). This patent describes an electronic device equipped with control circuitry that gathers Ambient Light measurements using a color ambient light sensor. These responses of the sensor are processed to generate a color rendering index for the ambient light, which is then used to correct the color of captured images via a color correction matrix, leading to more faithful color rendering. In our paper titled "Improving RGB Illuminant Estimation Exploiting Spectral Average Radiance" (Erba *et al.*, 2024b) we present a novel AWB method where the image acquired by a conventional high-resolution RGB color camera is combined with a low-resolution spectral image acquired by an Ambient Light Sensor, producing a high-resolution spectral image.

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Our approach focuses on three key points:

1. **Spatial Resolution for Input Sampling:** We investigate the optimal spatial resolution for sampling input images in terms of both RGB color and spectral information to maximize performance. By dividing the input image into patches and using these patches for training, we determine the most effective patch size for illuminant estimation.

2. **Illuminant Prediction Domain:** We explore whether it is more advantageous to predict the illuminant in the spectral domain or the RGB color domain. This investigation allows us to refine our model's approach to predicting illuminants, ensuring that the estimation is as accurate as possible in the RGB color space.

3. **Loss Function Domain:** Assuming that the illuminant is predicted in the spectral domain, we examine whether it is better to define the loss function in the RGB color domain or the spectral domain. This analysis helps to fine-tune our model's training process, leading to improved accuracy in the final illuminant estimation.

Our experiments, conducted on the NUS multispectral radiance dataset, demonstrate that the best results are achieved when the model is trained to predict the illuminant in the spectral domain using an RGB color loss function. This approach leads to a significant improvement in the mean recovery angular error, reducing it by 66% compared to the best-tested spectral method and by 41% compared to the best-tested RGB method.

AWB using spectral recovery from RGB data

A third approach is to use RGB data to recover spectral information, which can then be utilized to apply spectral methods for AWB.

This process begins with reconstructing the full spectral profile of the scene from the RGB image using techniques like spectral reconstruction algorithms. Our paper "Fast-n-Squeeze: Towards Real-Time Spectral Reconstruction from RGB Images" (Agarla *et al.*, 2022) introduces one such efficient algorithm for real-time spectral reconstruction from RGB images. The method combines a global RGB-to-spectral linear transformation matrix, estimated through Moore-Penrose pseudo-inverse (Penrose, 1955), with a lightweight convolutional neural network (CNN) for scaling the output (Iandola, 2016). The first part, "Fast," estimates the transformation matrix based on low-level image features, while the second part, "Squeeze," uses a CNN to refine the reconstruction through global scaling. The method, designed for the NTIRE 2022 Spectral Reconstruction Challenge (Arad *et al.*, 2022), achieves a balance between computational efficiency and reconstruction accuracy, offering superior performance with fewer artifacts compared to other state-of-the-art methods. Fast-n-Squeeze operates at 198 FPS on a GPU, making it highly suitable for real-time applications.

Alternatively, in our paper “RGB Illuminant Compensation Using Spectral Super-resolution and Weighted Spectral Color Correction” (Buzzelli *et al.*, 2023b) we estimate spectral information from RGB data and use it for illuminant estimation. The paper introduces a novel method for spectral illuminant correction in smartphone imaging, improving color accuracy by leveraging Spectral Super-resolution and Weighted Spectral Color Correction (W-SCC), which applies per-wavelength weight optimization to correct color discrepancies. Additionally, by combining the spectral illuminant estimation with RGB illuminant estimation, a joint estimation approach is also developed. To test the effectiveness of the approach, Moore-Penrose pseudo-inverse (Penrose, 1955) and a sensor sensor-independent AWB method (Bianco & Cusano, 2015) are employed respectively for spectral reconstruction and illuminant estimation. However, any algorithm could theoretically be adopted.

Through experiments on synthetic images, simulated with Huawei P50 camera sensor and Ambient Multispectral Sensors (AMS), the method shows significant reductions in colorimetric errors compared to traditional pipelines, achieving improved accuracy in color correction. The proposed W-SCC approach has applications in areas such as color analysis, computer vision, and industrial inspection, with potential for future enhancements through advanced optimization techniques and machine learning.

In general, once the spectral data is recovered, spectral-based methods are employed to estimate the scene illuminant with greater accuracy across multiple wavelengths. The refined illuminant estimation is then converted back to the RGB domain for color correction. This hybrid approach leverages the richer spectral information derived from RGB data to improve the accuracy of color compensation, combining the strengths of both RGB-based and spectral-based techniques.

Conclusions

This paper demonstrates the effectiveness of integrating multispectral information into RGB color constancy algorithms, significantly enhancing color accuracy under diverse lighting conditions. By extending traditional RGB-based methods to the multispectral domain and employing re-elaboration techniques, we achieved a substantial reduction in reproduction angular error. The use of ambient sensors and spectral recovery from RGB data further improved the precision of illuminant estimation. These advancements underline the potential of multispectral imaging to overcome the limitations of conventional RGB-based color correction, paving the way for more accurate and reliable color constancy in digital imaging. Future work will focus on refining these methods and exploring their application in various fields, including consumer electronics, remote sensing, and healthcare imaging.

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Metamerism in forensic medicine in imaging aspect

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Abstract

Metamerism in colours is a perceived matching of colors with different (nonmatching) spectral power distributions. Colors that match in this way are called metamers. As visual perception, different compositions of different wavelengths of light are perceived as one and the same color. In this study normal color vision and video recordings are compared with metamerism. Metamerism is different from color vision defects. What can be seen is the change in daylight over the course of the day due to changing lighting conditions and the change in metamerism in rooms with changing light sources. Therefore, one may see different colors in the video or photo than your eye (or brain) perceives. In forensic medicine, metamerism affects more than just eyewitness testimony. Metamerism, among other things, is crucial in the color assessment of the skin and organs, the evidence and the materials or surfaces present in life. Because of metamerism, surfaces that humans perceive as the same color can have different colors in digital photos and videos because cameras don't have color perception like the brain. Metamerism is a physiological phenomenon in humans. It also affects forensic doctors, who have to assess many things in their working lives in terms of color. Forensic physicians should be aware that metamerism effects can produce different results in all professional situations, as well as in people who are assessing the same thing.

Keywords: metamerism, human visual perception, forensic medicine, digital photos, digital videos

Introduction

Forensic medicine relies heavily on accurate color interpretation, whether in analyzing blood stains, fibers, or other materials critical to criminal investigations. Color distinctions can often be central to linking evidence to a crime scene or suspect, yet these assessments can be hindered by metamerism—a phenomenon in color science where two objects appear identical in color under certain lighting conditions, despite having different spectral properties (Fairchild, 2013). In forensic contexts, metamerism presents a significant challenge by creating potential discrepancies in color perception, especially when evidence is viewed under different lighting conditions or captured in video recordings (Smithson, 2005).

Human color vision, based on the response of three types of cone cells in the retina, adapts to varied lighting environments, a process known as color constancy (Brainard and Radonjić, 2016). Despite these adaptive capabilities, color perception is not infallible and can be subject to metameric matches, where two distinct colors appear indistinguishable to the observer. Such visual ambiguities can affect forensic judgments made based on color evidence, particularly when visual inspection is conducted without controlled lighting or when digital recordings are used as a basis for comparison. Video recordings, increasingly used in forensic settings, complicate matters further. Digital sensors and RGB-based color reproduction differ from human color perception, often accentuating or diminishing metameric effects, which can lead to color misinterpretations when evidence is reviewed (Cheung et al., 2004).

This paper investigates the effects of metamerism on color perception in both natural vision and digital video recordings, examining their impact on forensic analysis. By comparing these perceptual

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differences, this study seeks to provide forensic experts with insights into the potential pitfalls of relying on color-based evidence when metamerism is at play. Moreover, the paper will outline methodologies to mitigate these discrepancies, aiming to enhance the reliability and consistency of color evidence within the field of forensic medicine.

Definition and Explanation of Metamerism in Color Science

Metamerism is a fundamental phenomenon in color science that occurs when two distinct color stimuli appear identical to the human observer under certain conditions, even though they differ in their spectral compositions. This perceptual matching of colors that are not physically the same is a result of the way the human visual system processes light. The phenomenon of metamerism is central to understanding both normal color vision and the challenges it presents in color reproduction technologies, such as video imaging.

In the context of human vision, metamerism arises due to the limited number of photoreceptor types in the retina—typically three in trichromatic vision. These photoreceptors (cones) are sensitive to different portions of the visible spectrum, generally corresponding to the red, green, and blue regions of light. When two different spectral distributions of light stimulate these cones in such a way that the resulting response in each type of cone is identical, the two stimuli will be perceived as the same color, despite the fact that they may contain very different wavelengths. This is known as spectral metamerism.

Metamerism can also occur due to changes in the light source or viewing conditions. In practical terms, an object that appears to have a certain color under natural daylight may look entirely different under artificial lighting, even though the object's physical properties have not changed. This is a consequence of the differences in the spectral power distribution of light sources, which can alter the way colors are perceived. A key example is the phenomenon of illumination metamerism, where two objects under different light sources might appear the same under one light but differ under another, even though they are not physically identical.

Metamerism and its Relevance in Different Lighting Conditions

Metamerism is a phenomenon where two objects or colors, despite having distinct spectral power distributions, appear to match under a particular light source. This occurs because the human visual system is sensitive to certain wavelengths of light and processes them in a way that makes these different spectral profiles appear perceptually identical. In the field of color science, metamerism is a key concept, particularly when considering its implications for color perception and color matching in various practical contexts, such as in forensic science, digital imaging, and even everyday color reproduction.

The relevance of metamerism in different lighting conditions arises from the fact that the spectral composition of light varies greatly depending on the light source. For instance, natural daylight, incandescent bulbs, and fluorescent lights all emit light with different spectral distributions, which in turn affects how colors are perceived. While two objects might appear to match in one light condition, they may appear significantly different when illuminated by a different source. This variation in color perception is what makes metamerism a critical consideration in disciplines where precise color matching is required, such as in forensic medicine, where color consistency can be essential for the accurate interpretation of evidence.

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In the context of forensic science, metamerism presents both challenges and opportunities. Forensic investigators may rely on video recordings, photographs, or direct observations to match or identify evidence based on its color. However, the lighting conditions under which evidence is examined or recorded can drastically affect the accuracy of these color matches. A piece of evidence might appear to be a certain color under natural daylight, but when viewed under the artificial lighting of a crime scene, its color could shift, making it difficult to determine the true color of the object or its relationship to other pieces of evidence.

Several studies in color science have investigated how metamerism affects color matching in practical applications. For example, research has shown that even slight variations in lighting can cause significant changes in how objects are perceived in terms of color, leading to potential misinterpretations in forensic investigations (Wyszecki & Stiles, 2000). The use of standardized lighting conditions, such as the CIE Standard Illuminants, is one way to minimize these effects in color matching tasks, though it remains a challenge to replicate exact lighting conditions consistently in real-world settings.

Differences Between Recorded Video Colors and Real-World Visual Perception

The phenomenon of color perception in recorded video is notably different from that in the real world, a disparity that has important implications for fields such as digital media, forensic science, and color science. While our visual system perceives colors based on the interaction of light with surfaces and the processing of that light by the retina, video recordings represent a constrained version of reality, where color information is captured, processed, and displayed through a complex series of digital transformations. This section examines the differences between recorded video colors and real-world visual perception, focusing on the factors that contribute to these differences and the implications for accurate color reproduction.

In real-world visual perception, colors are influenced by a range of variables, including the spectral properties of light sources, the reflectance of surfaces, and the viewing conditions. The human visual system processes light using three types of cone cells (S-cones, M-cones, and L-cones), each sensitive to different parts of the visible spectrum. This trichromatic system allows for a nuanced interpretation of color based on the wavelengths of light that are absorbed or reflected by objects. Additionally, real-world perception accounts for various contextual cues, such as ambient lighting and surrounding colors, which contribute to our understanding of the color of an object in a dynamic, natural environment (Wyszecki & Stiles, 2000).

However, in video recordings, the representation of color is constrained by several technological factors. The most significant of these are the limitations of the imaging sensor, the color space used in digital encoding, and the display technology. Digital video cameras capture light using sensors that are typically limited to a specific range of wavelengths, resulting in a color gamut that may not fully replicate the richness of real-world colors. Moreover, the process of converting captured data into a digital format often involves color sampling, quantization, and compression, all of which introduce errors or approximations that can further alter the perceived color (Fairchild, 2013).

One of the primary challenges in matching recorded video colors to real-world colors is the issue of color space. Different video formats use different color spaces to encode color information. For instance, the commonly used RGB (Red, Green, Blue) color space represents colors as combinations of three primary colors, but it cannot capture all the colors that the human eye can perceive. Other color spaces, such as YCbCr or CIE XYZ, are often employed for more accurate color representation in specific contexts, yet they too have limitations when it comes to replicating the full spectrum of

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colors seen in natural settings. When video is displayed on a screen, the display device—whether a computer monitor, television, or smartphone—also introduces its own limitations, based on the color gamut of the screen and the properties of the light emitted from it. These factors all contribute to discrepancies between the colors recorded in a video and the colors perceived by the human eye in the real world.

Another critical factor in the disparity between recorded video colors and real-world visual perception is lighting. Real-world colors are highly dependent on the spectral distribution of light sources. For example, daylight has a balanced spectrum that provides a full range of wavelengths, leading to accurate color perception in natural conditions. In contrast, artificial lighting sources, such as fluorescent or incandescent bulbs, emit light with a more limited spectral range, which can significantly alter how colors appear. Video recordings, however, are typically made under specific lighting conditions that may not replicate the full range of real-world lighting, leading to potential color shifts when viewed under different light sources. Moreover, the calibration of cameras and displays plays a significant role in determining how accurately colors are captured and reproduced in recorded video. Without proper calibration, even under controlled lighting conditions, color discrepancies can occur (Hunt, 2004).

The Significance of Accurate Color Recognition in Forensic Contexts

Color recognition plays a crucial role in forensic science, where accurate identification and interpretation of evidence can be pivotal for solving criminal cases. Whether in the identification of objects, the analysis of crime scene photos or video footage, or in the comparison of physical evidence, color is often one of the key attributes used to distinguish between materials, objects, or individuals. However, the accuracy of color recognition in forensic contexts is subject to a range of variables that can affect both the perceived and recorded color, including lighting conditions, metamerism, and the limitations of technology used in evidence collection.

The perception of color can be highly influenced by the lighting under which it is viewed. Different light sources—whether natural sunlight, artificial indoor lighting, or streetlights—emit light with varying spectral compositions, leading to differences in the perceived color of objects. This phenomenon, known as *metamerism*, occurs when two objects appear the same under one light source but are actually different when illuminated by a different light. In forensic contexts, this can complicate the interpretation of evidence, especially in situations where photographs or video recordings are used to document the scene. Without a proper understanding of metamerism and the factors influencing color perception, forensic professionals may make inaccurate conclusions based on misleading color matches. Thus, it is essential for forensic experts to carefully control and standardize lighting conditions when documenting evidence and to take into account the potential for color shifts under different illuminants (Wyszecki & Stiles, 2000).

In the digital age, forensic investigators often rely on photographic and video evidence to support their findings. While these technologies offer invaluable tools for documenting and analyzing crime scenes, they also introduce additional challenges in terms of color recognition. The cameras and sensors used in video recordings capture light in a way that may not accurately represent the full spectrum of colors seen by the human eye. Digital sensors have limited color gamuts, and the color accuracy of recorded images is influenced by factors such as sensor technology, white balance settings, compression algorithms, and display technology. These technological limitations can result in discrepancies between the color of an object in the recorded image and its true color in the real world, potentially leading to errors in forensic analysis (Fairchild, 2013).

Another challenge lies in the use of different color spaces and standards in forensic imaging. Forensic photographs or video recordings may use a variety of color spaces such as RGB, YCbCr, or CMYK, each of which has different methods of encoding and representing color. In practice, this means that the same scene may look different depending on the technology used to capture and display the image. Inconsistent color rendering across different media can lead to challenges when comparing physical evidence with its digital representations. Therefore, ensuring proper calibration of imaging devices and using standardized color spaces are vital for improving the accuracy of color recognition in forensic contexts (Hunt, 2004).

Accurate color recognition is also crucial in specific forensic disciplines, such as toxicology, pathology, and serology. For instance, the analysis of bloodstains, bodily fluids, or drug residues may rely on subtle color differences that are difficult to discern under improper lighting conditions or with inaccurate imaging equipment. A bloodstain that appears dark red in one lighting condition might be mistaken for a different substance if viewed under another light source. Similarly, changes in color during the chemical analysis of substances can be used to identify toxins or drugs, providing critical information for forensic investigations. The inability to accurately perceive or record these color changes can hinder the ability to make reliable determinations, potentially affecting the outcome of a case.

Challenges Posed by Metamerism in Forensic Investigations

In forensic investigations, accurate color recognition is often essential for identifying key evidence, such as blood stains, clothing, or vehicle paint. For instance, in cases involving hit-and-run accidents, forensic experts may rely on the color of a vehicle to match witness testimonies or surveillance footage. Similarly, in homicide cases, forensic teams might identify stains or residue that match the color of a substance found at the crime scene. However, metamerism complicates this process, as objects that seem to match in color under one lighting condition may appear different under another, leading to potential misinterpretations. For example, a piece of evidence that appears red under daylight may appear brown or orange under artificial light, making it difficult to accurately link it to a suspect or to confirm the presence of a specific substance (Wyszecki & Stiles, 2000).

The challenge of metamerism is particularly pronounced in forensic photography and videography. Forensic investigators often rely on digital images to document crime scenes, suspect profiles, or objects of interest. However, digital cameras and sensors have their limitations in capturing and reproducing the full spectrum of colors visible to the human eye. Factors such as sensor technology, white balance, and the color space used in digital encoding can all distort the way colors are recorded. For example, cameras may capture the color of an object within a limited color gamut, meaning that some colors may not be accurately reproduced, leading to potential misidentifications or inconsistencies between digital images and real-world appearances (Fairchild, 2013). This issue is compounded by the fact that video and photographic evidence is often viewed on a variety of screens—such as computer monitors, televisions, or smartphones—that each have different color calibration settings and gamuts. As a result, forensic professionals may struggle to reconcile discrepancies between the color observed in the recorded images and the actual color of the object in question, making it difficult to draw definitive conclusions.

Lighting conditions are another key factor that exacerbates the effects of metamerism in forensic investigations. Natural sunlight contains a broad spectrum of wavelengths, which provides a relatively accurate representation of color, whereas artificial light sources—such as incandescent bulbs, LED lights, or fluorescent lighting—can have spectral distributions that are more limited. This discrepancy can cause significant color shifts when objects are viewed under different lighting conditions (Hunt, 2004).

Metamerism also presents challenges in forensic toxicology and serology, where the color of certain substances, such as bodily fluids, drugs, or chemical residues, can play a critical role in identifying or confirming their presence. Subtle changes in color are often used to detect the presence of specific substances, such as when reagents are added to blood or urine samples. Inaccurate color recognition due to metamerism can lead to false negatives or positives, potentially undermining the reliability of forensic analyses. For instance, a chemical reaction that produces a color change in a substance may be misinterpreted if the observer is unaware of the impact of lighting or camera settings on the perception of color (Wyszecki & Stiles, 2000).

Metamerism in Video Imaging Systems

In video imaging, metamerism arises due to the limitations of the imaging sensors and the color reproduction capabilities of display devices. Digital cameras and video systems typically rely on three-color sensors (red, green, and blue), which attempt to mimic the trichromatic nature of human vision. However, these systems face inherent challenges in capturing the full range of spectral information that the human eye can perceive. The limited number of sensors cannot fully replicate the nuanced responses of the human photoreceptors, which are more sensitive to a broader range of wavelengths and subtle spectral variations (Fairchild, 2013).

Moreover, video imaging involves several stages of processing—such as color filtering, encoding, compression, and display rendering—that can further exacerbate metameric effects. For example, in many video systems, the color gamut of the camera sensor is narrower than that of the human eye, leading to color clipping where certain hues are not captured or reproduced accurately. Additionally, differences in the display technology, such as LCD, OLED, or CRT, introduce further metameric distortions due to varying color gamuts, contrast ratios, and light emission properties (Poynton, 2003).

Consequences of Metamerism for Forensic Practitioners

In forensic contexts, this can pose a major problem. Evidence that appears to match under one light condition may actually differ when the light changes. This is particularly crucial in the analysis of color-based evidence, such as fibers, paint chips, or other materials, where color matching is used to link suspects, objects, or crime scenes. Forensic practitioners may mistakenly conclude that two samples are identical when they are not, or they might fail to identify a match because the samples appear different under different lighting.

For example, in forensic trace evidence analysis, where fibers and paint samples are compared for matching, the color of the sample may vary depending on the light source. What initially appears to be a perfect match under one light condition might diverge significantly under another, leading to false exclusions or mistaken identifications. This is especially relevant in cases involving low-light conditions or when samples are compared in laboratories with controlled lighting that differs from real-world lighting (Godwin et al., 2017).

Implications for Forensic Photography and Documentation

Forensic photography plays an integral role in the documentation of crime scenes and evidence. However, metamerism presents a challenge for forensic photographers who must capture accurate representations of color in evidence. Since photographic equipment is limited by its own color response characteristics, the captured image may not always reflect the true color of the evidence, even if the lighting conditions are consistent. The color distortions introduced by the camera sensor, combined with the potential effects of metamerism, can result in photographs that inaccurately represent the color of critical forensic evidence (Gibson, 2016).

Metamerism and the Reliability of Color Matching in Forensic Identification

The reliability of color matching in forensic identification can be compromised by metamerism, especially in the analysis of trace evidence such as fibers, paints, and dyes. These types of evidence are often used to link a suspect to a crime scene, and color matching is one of the primary methods for comparison. However, metamerism introduces an additional layer of uncertainty in these comparisons. Even if two samples appear to match in color under one light condition, there may be subtle differences in their spectral composition that are not perceptible under that light but could be revealed under different conditions.

Forensic practitioners must therefore consider not only the visual appearance of evidence under a specific light but also the potential for metamerism when making conclusions about matches. This may involve using standardized lighting conditions or sophisticated color measurement tools to ensure that color matching is based on more than just subjective visual perception. Moreover, forensic scientists must be aware of the limitations of their tools and the potential for metameric effects to alter their conclusions (Godwin et al., 2017). This highlights the need for careful and precise documentation of the lighting conditions and photographic techniques used in evidence analysis, as well as the application of additional color measurement techniques, such as spectrophotometry, to verify color matches.

Mitigating the Effects of Metamerism in Forensic Practice

To mitigate the effects of metamerism, forensic practitioners can adopt several strategies. One approach is to standardize the lighting conditions under which evidence is analyzed and documented. Using controlled lighting environments, such as standardized illuminants or light booths, can help ensure that the color of evidence is perceived consistently. Additionally, forensic labs may employ color measurement tools, such as spectrophotometers, to objectively capture the spectral properties of samples, allowing for more accurate comparisons that account for metamerism (Poynton, 2003). These tools provide quantitative data that can be used to supplement visual color matching and reduce the subjectivity inherent in human color perception.

Furthermore, forensic practitioners should be trained to recognize the potential for metamerism and its consequences for color matching. This includes being aware of the specific limitations of photographic equipment and understanding the importance of environmental factors that may influence color perception. By incorporating these practices, forensic professionals can improve the accuracy and reliability of color-based evidence analysis, thereby reducing the risk of errors caused by metamerism.

Conclusions

In this study, we have examined the phenomenon of metamerism in normal color vision and its implications for video recordings, specifically in the context of forensic medicine. Our analysis reveals that metamerism plays a crucial role in both human color perception and the accuracy of

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video-based evidence, particularly in situations where precise color matching is essential for forensic investigation. It is evident that metamerism introduces a potential source of error, as forensic experts may misinterpret the colors of items under different lighting conditions, which may differ substantially from the actual appearance under natural light. Furthermore, comparison with video recordings highlights additional complexities in forensic contexts. Video systems, depending on their camera technology and lighting conditions, may not faithfully reproduce the colors seen by the human eye. The resolution, compression, and processing of video signals may alter the perceived color, making it susceptible to metameric effects. Consequently, this discrepancy raises concerns about the reliability of video footage in forensic investigations, especially when color plays a critical role in identifying individuals, objects, or events. (Knoblauch et al. ,2001) (Wyszecki et al , 2000). To address these challenges, it is essential for forensic practitioners to consider the potential influence of metamerism when interpreting color-related evidence.

The recognition and understanding of metamerism in both normal color vision and video recordings are critical for enhancing the accuracy of forensic analyses. By acknowledging the limitations of color perception and the potential distortions in video recordings, forensic experts can make more informed decisions, leading to more reliable conclusions in legal proceedings. Future advancements in technology and improved forensic protocols will likely mitigate these challenges, ensuring that color-based evidence remains a trustworthy component of forensic investigations.

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Shades of Perception: Understanding Color Vision Impairments in Multiple Sclerosis

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Abstract

Multiple sclerosis (MS) is a chronic autoimmune disease characterized by demyelination and axonal damage within the central nervous system, leading to an array of symptoms. The impact of MS on sensory perception - particularly color vision - has garnered increasing attention. In the literature 65% of People with MS (PwMS) failed at least one of the color tests, indicating huge color vision abnormalities, ranging from subtle deficits to pronounced impairments, in a big percentage of them. The etiology of these abnormalities remains multifactorial, with demyelination of optic nerve fibers, retinal ganglion cell dysfunction, and cortico-cortical communication implicated in their pathogenesis. Emerging evidence suggests a potential association between specific patterns of retinal nerve fiber layer thinning and the severity of color vision deficits, highlighting the utility of optical coherence tomography in elucidating underlying mechanisms.
Various tests that measure the relationship between physical stimuli and psychological responses, including color discrimination and hue discrimination tasks, have demonstrated that the deficits of color could be useful in finding some abnormalities. The most commonly reported deficits include reduced color contrast sensitivity, impaired color discrimination along the blue-yellow axis, and alterations in color appearance such as color desaturation and color distortion.
The impact of MS-related color vision impairment extends beyond visual perception, influencing daily activities such as driving, reading, and navigating the environment. Consequently, a comprehensive assessment of color vision perceptions should be integrated into routine clinical evaluations to facilitate early detection of sensory abnormalities, optimize treatment planning, and improve patient outcomes.
This article is a proof of concept to evaluate the relationship between visual deficits and color perception abnormalities, evaluate the tests and tools available, and open the possibility of introducing the color perception assessment in the clinical anamnesis to evaluate how to use that information for future rehabilitation programs. Future research utilizing advanced imaging techniques and behavioral measurements is needed to better understand the underlying pathophysiology and improve outcomes.

Keywords: Color vision, Multiple sclerosis, vision symptoms

1. Introduction

Multiple sclerosis (MS) is a chronic, neurodegenerative autoimmune disease characterized by demyelination and axonal damage within the central nervous system, leading to a myriad of neurological symptoms that sometimes can compromise also the visual pathway (Dhanapalaratnam R et al. 2022). Visual symptoms are diverse and can have a significant impact on daily life (Mowry et al., 2009; Garcia-Martin et al., 2013). One of the most common manifestation, present in 20% of PwMS (Costello, 2012) and often the first symptom, is optic neuritis, characterised by a sudden and painful loss of vision usually affecting only one eye. This condition results from inflammation of the optic nerve, leading to blurred vision, central scotomas and sometimes temporary complete loss of vision. Another visual symptom is diplopia, or double vision, which results from weakening or incoordination of the eye muscles due to lesions in the brain that controls these muscles, causing difficulty in maintaining a single visual image. Lastly, many PwMS suffer from nystagmus, which involves involuntary and rapid eye movements that can compromise visual stability, resulting in difficulty visualizing and processing elements in the visual field and thus leading to problems with focusing and depth perception (Dhanapalaratnam R et al. 2022).

The impact of the disease on sensory perception, especially color vision, has gained attention, as deficits in color processing can exacerbate visual symptoms and negatively affect perceived quality of life (Balcer et al., 2015, Jasse et al., 2013). Color is a fundamental element of everyday life, and its color components can significantly influence the emotions and behaviors of human beings (Bortolotti et al., 2022). Recent studies have begun to explore the extent to which MS affects color vision, revealing potential correlations between disease progression and sensory deficits (Martínez-Lapiscina et al., 2014). In the literature, 65% of PwMS failed at least one of the color vision tests, indicating significant color vision abnormalities, ranging from subtle deficits to pronounced impairments, in a large percentage of them (Anssari, N., et al. 2020). The importance of early detection and intervention cannot be overstated, as timely management of MS-related sensory impairments can help mitigate their impact on daily activities (Balcer et al., 2017).

This article aims to discuss potential mechanisms underlying these color deficits, evaluate the tests and clinical exams useable, and highlight the significance of incorporating sensory and color assessments into routine clinical evaluations for PwMS (Villoslada et al., 2012). By shedding light on this often-overlooked aspect of MS, we want to contribute to a more comprehensive understanding of the disease and improve the process of care (Saidha et al., 2011).

2. Color deficits in MS: what and when

The prevalence of color vision deficits in MS is striking, with studies reporting rates ranging from presence in 20% to 70% PwMS (Harrison AC et al. 1987; Villoslada et al., 2012). This wide range reflects the variability in assessment methods and populations studied, but also underscores the significance of this category of symptom. What's particularly noteworthy is that these deficits can occur early in the disease course, sometimes even before other neurological symptoms become apparent (Moura et al., 2008). This early manifestation suggests that color vision testing could potentially serve as an early marker for MS, opening up new avenues for early diagnosis and intervention.

Color vision deficiencies may manifest as difficulties in distinguishing between certain hues, reduced color saturation, and overall diminished color perception (Moura et al., 2008).

When we delve into the specifics of the color vision category, a consistent pattern emerges. Multiple studies have reported a predominant impairment along the blue-yellow axis of color vision (Pache et al., 2003; Moro et al., 2007; Rocca et al., 2016). This selective vulnerability is intriguing from a neurophysiological perspective. The human visual system processes color information through three main pathways: the magnocellular (responsible for motion and depth perception), parvocellular (involved in red-green color discrimination and fine detail), and koniocellular (which handles blue-yellow discrimination). The preferential involvement of the blue-yellow axis suggests that the koniocellular pathway may be particularly susceptible to MS-related damage.

But why should this be the case? One theory posits that the koniocellular pathway, which consists of smaller caliber fibers, may be more vulnerable to the demyelinating process (Evangelou et al., 2001). Another possibility is that the blue-yellow system, being evolutionarily older and less redundant than the red-green system, has fewer compensatory mechanisms to counteract disease-related damage. Whatever the underlying reason, this pattern of deficit provides valuable insights into the selective impacts of MS on neural circuits.

Last, but not least, emerging research suggests intriguing links between color vision deficits and other aspects of MS pathology. For instance, Wieder et al. (2013) reported correlations between color vision deficits and performance on cognitive tests, particularly in information processing speed and visual memory. This connection hints at shared neural substrates between color processing and certain cognitive functions, offering a new perspective on the widespread effects of MS on the brain (Martínez-Lapiscina et al., 2014).
From a clinical standpoint, color vision deficits' assessment holds promise as a tool for monitoring disease progression and treatment efficacy. Moro et al. (2007) found that the severity of color vision deficits correlated with higher scores on the Expanded Disability Status Scale (EDSS), a standard measure of disability in MS. This correlation suggests that color vision testing could serve as a sensitive, non-invasive marker of overall disease severity. Further studies will be needed to assess which of theories is the most robust and use this information with all the others symptoms information, included the cognitive ones, to predict the possibility of the onset of colour vision deficit and/or create protocols that promote mechanisms of neuroplasticity and diaschisis.

The etiology of color vision deficits in MS

The origins of color perception abnormalities MS are complex and multifactorial, with factors such as optic nerve demyelination, retinal ganglion cell dysfunction, and disrupted cortico-cortical communication playing key roles in their development (Sanchez-Dalmau et al., 2018).
The visual system, with its intricate network of neurons extending from the retina to the visual cortex, is often compromised in MS, as the disease targets myelin sheaths that insulate neural pathways. This autoimmune assault disrupts the transmission of visual information, including color signals, leading to significant sensory impairments (Balcer et al., 2015). Optic neuritis, as common symptom of MS, results in inflammation and optic nerve damage that frequently impairs color vision (Balcer et al., 2015). Emerging evidence also suggests that specific patterns of retinal nerve fiber layer (RNFL) thinning ar related to neurodegeneration, disease progression, and to the severity of color vision deficits (Saidha et al., 2011). Notably, RNFL thinning is observed not only in PwMS with optic neuritis but also in those without, indicating the presence of subclinical disease activity (Al-Mujaini et al.,2021; Petzold et al., 2010; 2017) that will be investigated deeply.
Despite the advances, our understanding of color vision deficits in MS remains incomplete. The exact mechanisms underlying these deficits are still debated. While demyelination of optic nerve fibers is likely a primary factor, other processes such as chronic axonal degeneration and cortical reorganization may also play roles (Backner et al., 2022). The relative contributions of these factors, and how they interact throughout the disease, remain active areas of research.

The color vision assessment

The assessment of color vision deficits in multiple sclerosis (MS) has undergone significant evolution, reflecting advancements in our understanding of color perception and improvements in technological capabilities (See table 1).
The Farnsworth-Munsell 100 Hue Test (FM100), developed in the 1940s, remains a gold standard for comprehensive color discrimination evaluation. Research by Sisto et al. (2005) demonstrated that people with MS (PwMS) exhibit significantly higher error scores on this test compared to healthy controls, particularly along the blue-yellow axis. Furthermore, Villoslada et al. (2012) reported color deficits in 42.5% of PwMS assessed with the FM100. While this test provides detailed insights and is sensitive to color vision changes in MS, its administration can be time-consuming and challenging for some individuals.
In conjunction with the FM100, studies utilizing Ishihara plates (Piro A. et al. 2019) have also identified color deficits in approximately 45% of PwMS (Martínez-Lapiscina et al., 2014). This test primarily assesses red-green deficiencies and is widely recognized for its clinical utility.

Recently, computerized assessments such as the Cambridge Colour Test (CCT) have gained prominence due to their ability to deliver precise, quantitative measurements of color discrimination thresholds. Moura et al. (2008) utilized the CCT to reveal elevated chromatic discrimination thresholds in PwMS, particularly along the protan and tritan axes, which correspond to red and blue deficiencies, respectively. These computerized tests not only provide more granular data but also facilitate standardization across research studies and clinical applications (Barbur et al., 2021).

Another innovative tool is the Cone Contrast Test (CCT), which evaluates the function of individual cone types in the retina and offers quantitative measurements of color and contrast sensitivity (White KM et al. 2023). Martínez-Lapiscina et al. (2014) demonstrated impaired function across all three cone types in PwMS, with the most pronounced deficits observed in S-cones responsible for blue-yellow discrimination. This finding aligns with documented impairments along the blue-yellow axis and suggests that the Cone Contrast Test could serve as a valuable tool for monitoring treatment efficacy in clinical trials, potentially offering a more sensitive measure of visual pathway integrity than traditional visual acuity tests (Nolan et al., 2018).

Beyond psychophysical assessments, electrophysiological methods such as Visual Evoked Potentials (VEPs) provide direct measures of neural activity in response to visual stimuli. Sartucci et al. (2001) found delayed latencies and reduced amplitudes in chromatic VEPs, particularly for blue-yellow stimuli, indicating altered neural processing of color information in MS—even when overt clinical symptoms are absent (Thurtell et al., 2009).

The integration of color vision assessments with advanced imaging techniques like optical coherence tomography (OCT) and functional MRI holds promise for elucidating the structural and functional correlates of these deficits (Saidha et al., 2011; Kuchling et al., 2017). OCT has emerged as a valuable tool for assessing retinal changes in MS, providing high-resolution images that allow for quantification of retinal layer thickness (Costello et al., 2006; Anssari et al., 2019). This non-invasive technique has been instrumental in identifying correlations between retinal nerve fiber layer thinning and visual function, enhancing our understanding of the pathophysiological mechanisms underlying these deficits (Balk et al., 2014). Additionally, OCT measurements have been shown to correlate with key MS outcomes, including low-contrast visual acuity, disability progression, response to disease-modifying therapies, and brain atrophy metrics (Britze et al., 2018). By integrating OCT into routine clinical evaluations alongside fMRI, clinicians can better monitor disease progression and tailor interventions to address sensory impairments in PwMS.

There is also an urgent need for standardized protocols for assessing color vision in MS to facilitate comparisons across studies and enable broader clinical application (Balcer et al., 2017). Perhaps most excitingly, therapeutic interventions specifically targeting color vision deficits remain largely unexplored. While existing MS treatments may indirectly benefit color vision by reducing overall disease activity, targeted strategies aimed at preserving or restoring color perception could significantly enhance quality of life. Such interventions might include neuroprotective approaches focused on maintaining koniocellular pathway integrity or rehabilitative strategies that leverage neural plasticity to improve color processing capabilities (Cortese et al., 2021).

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Name of the Test	Acronyms	Reference	Outcome
Farnsworth-Munsell 100 Hue Test	FM100	Villoslada et al. (2012)	Assesses comprehensive color discrimination; higher error scores indicate color vision deficits.
Ishihara Plates	-	Piro et al. (2019)	Identifies specific color vision deficiencies; primarily assesses red-green color blindness.
Cambridge Colour Test	CCT	Moura et al. (2008)	Measures chromatic discrimination thresholds; higher thresholds indicate greater color vision impairment.
Cone Contrast Test	CCT	Martínez-Lapiscina et al. (2014)	Evaluates the function of individual cone types; impaired results indicate deficits in color and contrast sensitivity.

Table 7 list of test

Discussion

Color vision deficits in MS represent a complex and multifaceted aspect of the disease that warrants continued scientific attention. The prevalence of these deficits, ranging from 20% to 70% of PwMS (Villoslada et al., 2012), underscores their significance in the clinical presentation of MS. The consistent finding of predominant impairment along the blue-yellow axis (Pache et al., 2003; Moro et al., 2007; Rocca et al., 2016) provides valuable insights into the selective vulnerability of neural pathways in MS, particularly the koniocellular pathway. The evolution of assessment methods, from the classic Farnsworth-Munsell 100 Hue Test to more advanced computerized tests like the CCT (Moura et al., 2008) and the CCT (Martínez-Lapiscina et al., 2014), has greatly enhanced our ability to quantify and characterize these deficits. Electrophysiological methods such as VEP (Sartucci et al., 2001) have further elucidated the neural basis of color vision impairments in MS. The implications of color vision deficits extend beyond visual perception, impacting PwMS' quality of life and potentially serving as markers of overall disease progression (Balcer et al., 2015; Jasse et al., 2013). The observed correlations between color vision deficits and cognitive performance (Wieder et al., 2013) hint at shared neural substrates, offering new perspectives on the widespread effects of MS on the brain.

While significant progress has been made, several crucial areas require further investigation. The exact mechanisms underlying color vision deficits in MS, including the relative contributions of demyelination, axonal degeneration, and cortical reorganization, remain to be fully elucidated (Backner et al., 2022). Longitudinal studies tracking the evolution of these deficits over the course of MS could provide valuable insights into disease progression and visual pathway integrity (Gabilondo et al., 2014). The integration of color vision assessment with advanced imaging techniques, such as optical coherence tomography (OCT) and functional MRI, holds promise for uncovering structural and functional correlates of these deficits (Saidha et al., 2011; Kuchling et al., 2017). Furthermore, the development of standardized protocols for assessing color vision in MS could facilitate more widespread clinical use and enable more robust cross-study comparisons (Balcer et al., 2017). Perhaps

most excitingly, the field of therapeutic interventions specifically targeting color vision deficits in MS remains largely unexplored. Future research in this area could potentially lead to significant improvements in people's visual function and overall quality of life, ranging from neuroprotective strategies aimed at preserving koniocellular pathway integrity to rehabilitative approaches leveraging neural plasticity (Cortese et al., 2021).
In conclusion, color vision deficits in MS represent a rich area of study that intersects neurology, ophthalmology, and cognitive science. The early manifestation of these deficits, sometimes preceding other neurological symptoms, suggests their potential as early markers for MS. Continued research in this field promises not only to enhance our understanding of MS pathophysiology but also to improve patient care through better diagnostic, prognostic, and therapeutic approaches.

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Color Preferences of University Students in Dormitory Rooms

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Abstract

While color preference studies in interiors generally depend mostly on hues, some recent studies have shown that saturation and lightness levels of colors are also important. Dormitory rooms are designed generic and users usually add customized design pieces to increase individuality, attachment and belonging. Thanks to the dormitory users' color choices on items they can change, their space becomes a living, dynamic, and individualized place. In short, university students transfer parts of their identities by choosing some colors in their dormitories. In order to see the extent of color choices and to explore a consensus on color design in dormitories, a color choices study has been designed. In this study, students in university dormitories were asked to choose one color chip for 12 different surfaces from 66 predetermined color chips. Participants in this study are students who have accommodated in dorm rooms for a certain period of time and use the room constantly. No reference to the space was given in terms of color and material. Thus, color choices that could harmonize with any pre-given surface were avoided. These 66 ready-made colors indicate different hue, lightness and saturation levels using the CIELAB gamut. Twelve surfaces were drawn from the dormitory room with the adapted version of a two-dimensional image of, a real four-person dormitory room, which is used for students' convenience and ease of adaptation. All areas except two surfaces were selected as high lightness. There is a significant relation between color preferences and saturation except for one surface.

Keywords: color attributes, color preferences, lightness, saturation, university students.

Introduction

The beginning of color preferences dates back to the 1800s (Hurlbert and Ling, 2012). Color preferences observe the most preferred colors by simply inquiring about the favorite colors of individuals. One of the first studies on color preferences mentions Jastrow's experiment, in which participants were asked to choose their most preferred color from 12-piece sets of color chips (Dorcus, 1926). Eysenck (1941) tried to formulate a universal order of color preferences, starting from the most preferred to the least preferred colors. On the other hand, they reach a consensus that blue and green are the most preferred colors in general, and yellow and yellow-green are the least preferred (Guilford and Smith, 1959; Palmer and Schloss, 2010; Hurlbert and Ling, 2012).

Color Preference Studies in the Built Environment

The primary color preference studies focus only on the favorite color in a generic form. They mainly questioned preferences by showing the participants color chips. However, context plays a significant role in preferences, especially when we consider the real-world environment, where none of the colors take place as a single piece of chip of a specific size. The area, proximity, relative percentage of colors and the habitat (lighting, shadows, tint and shades of the colors, texture, materials) of the used colors make a significant difference. An individual's favorite colors vary depending on the context. For instance, even though a person's favorite color is pink, same person might prefer dark colors for clothing. Thus, contexts do matter largely in color preferences. Many different contexts are studied in the literature such as clothing (Roberts, Owen and Havlicek, 2010), food coloring industry (Lakshmi G., 2014), furniture and textile development (Fasllija, Olguntürk and Güvenç, 2020), built environment (Kaya and Crosby, 2006; Manav, 2007; Yıldırım, Akalın-Başkaya and Hidayetoğlu, 2007; Yıldırım, Hidayetoğlu and Çapanoğlu, 2011; Yıldırım, Çağatay and Ayalp, 2015; Van der Voordt, Bakker and De Boon, 2017; Torres et al., 2020; Mousavi Samimi and Sadraei Tabatabaei, 2022) are discussed in relevant literature.

Although there are many contributing factors to color preference studies, the color phenomenon has its attributes that have an impact on color preference studies (Alexander and Shan Sky, 1976; Camgöz, Yener and Güvenç, 2002; Gyu Park, 2014). Sir Isaac Newton's development of color spectrum introduced one of the attributes of color: Hue. Hues are categorized into chromatic colors and achromatic (without hues) colors. The chromatic colors are red, orange, yellow, green, blue, and purple, also called the rainbow or spectral colors (Agoston, 1979); whereas white, black, and grey are considered as achromatic colors. Color studies, especially color preferences, are mainly based on chromatic and achromatic colors. However, there are two factors more critical for color preference studies: Lightness (value) and saturation (chroma) (Alexander and Shan Sky, 1976). Lightness is the distance of how close a color is to white and black. The dark colors have low lightness, whereas light ones have high lightness and saturation is the intensity of color. The vivid colors have higher saturation (Agoston, 1979).

Color preferences about perceptual attributes of color in specific built environment studies are very limited in the literature. Mousavi Samimi and Sadraei Tabatabaei (2022) mention that preschool children prefer high lightness and saturation for a playground. The same results are obtained by Jiang et al. (2020) in adolescent room furniture with children. Children preferred low blackness and high chromaticness (Jiang et al., 2020). On the other hand, Gyu Park (2014) found that children prefer high lightness with yellow hues and high saturation with blue hues.

The various typologies of spaces show that they have different needs. While a design works optimally for a particular type of space, it may need to be revised for another space. Colors are one of the main design elements in the built environment, and users' needs and preferences with the availability and usability of colors should be decided at the beginning of the design procedure. Designers are primarily concerned about color selection since it requires an educated gaze. Designers prefer to use achromatic colors with simple hues as an accent color within spaces. Nevertheless, the users are not satisfied with the usage of dominantly achromatic colors and color preference studies mainly focused on this issue. Recent color preference studies deal with specific typologies such as cafes and restaurants (Yıldırım, Akalın-Başkaya and Hidayetoğlu, 2007), hotels (Yar Bilal, Aslanoğlu and Olguntürk, 2022), shopping malls (Kaya and Crosby, 2006), adolescent room (Jiang *et al.*, 2020), educational environments (Yıldırım, Çağatay and Ayalp, 2015), nursing homes (Torres *et al.*, 2020), different parts of interiors (Kaya and Crosby, 2006; Van der Voordt, Bakker and De Boon, 2017), living rooms (Manav, 2007; Yıldırım, Hidayetoğlu and Çapanoğlu, 2011), playgrounds (Mousavi Samimi and Sadraei Tabatabaei, 2022) and residential rooms (Ulusoy, Olguntürk and Aslanoğlu, 2020). Color preferences in the built environment were investigated using various methodologies as measurement, such as painting a massive wall in the real environment to ask participants about their preferences and considering the existing surroundings of that space, as Yıldırım et al. (2007) did, asking participants to choose colors from a simulation of the interior, as Jiang et al. (2020) did, or asking participants to select the printed versions of the different color combinations for a place, as Torres et al. (2020) did. Thanks to the advancements in technology, new methods are being introduced still.

Within the scope of this article, dormitories are selected as the setting since they are semi-public spaces that serve university students for a specific period of time. The design of a dormitory is different from that of a hotel room because hotels are designed to provide short-term accommodation and residents may be indifferent to them due to the time limit. Also, public and private needs should be considered simultaneously for a dormitory complex since a typical dormitory is composed of social areas (public) and a sleeping area (private). The sleeping quarters are designed as private parts in the residential area, and the social gathering areas should be designed according to the needs of the students. In this study, the sleeping quarters are the central research area since university students spend most of their time studying, eating, and sleeping in their rooms. This makes a sleeping quarter more than a simple sleeping unit, and yet what designers generally do is put simple furniture in the room. However, students want to be attached to the place, privatize, and personalize the space. Color is one of the design elements that can be easily changed. Thus, the question of which colors university students prefer for their dormitory rooms is an area that is yet to be studied more in the literature, and we aim to find a preferred color design for a dormitory room.

Methodology
The experiment was approved by the Bilkent University Ethics Committee. Participants of this study are the university students who accommodated, at least one semester in the dormitories of the university. The setting of the experiment was designed as an online platform. Despite the slight color inaccuracy caused by the varying electronic devices participants used, the number of participants was large enough to assure sufficient consistency of color perception among different devices. The aim of the study is to find an answer to the following questions:

Q1: Do university students prefer high over low lightness for their dormitory rooms?

Q2: Do university students prefer high over low saturation for their dormitory rooms?

Q3: Is there any significant relationship between saturation and lightness in terms of university students' preferences?

The data was collected and 200 students participated the experiment but only 192 participants were eligible. Eight participants were eliminated because one participant decided not to finish the study and seven participants turned out to be color blind according to Ishiara's Color Blindness Tests (Clark, 1924).

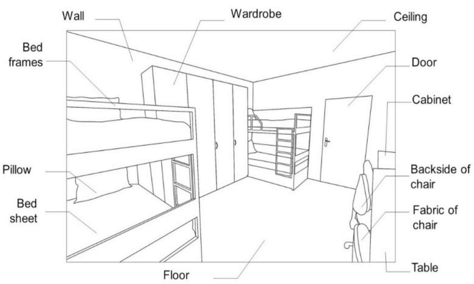

Figure 1. Two-dimensional line image

Figure 2. Dormitory room of Bilkent University

Participants were asked to fill out the consent form, demographic data sheet, Ishiara's Test, and the two-dimensional line image (Figure 1). The two-dimensional line image is originally from one of the dormitories of Bilkent University (Figure 2). For the final part of the experiment, participants selected their preferred color among given 66 color chips from the CIELAB Gamut (Figure 3) The lightness in CIELAB is denoted by the L* and saturation is the difference between a* and b* where -a* is green, +a* is red, +b* is yellow and -b* is blue hues. The central part of CIELAB gamut symbolizes achromatic colors (Schanda, 2007). The colors were selected with equal mathematical distances.

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	a=40			a=20			a=0			a=-20			a=-40		
	L	a	b	L	a	b	L	a	b	L	a	b	L	a	b
L=80	80	40	-20	80	20	-20	80	0	-20	80	-20	-20			
				80	20	0	80	0	0	80	-20	0	80	-40	0
				80	20	20	80	0	20	80	-20	20	80	-40	20
							80	0	40	80	-20	40	80	-40	40
L=60	60	40	-40	60	20	-40	60	0	-40						
	60	40	-20	60	20	-20	60	0	-20	60	-20	-20			
	60	40	0	60	20	0	60	0	0				60	-40	0
	60	40	20	60	20	20	60	0	20				60	-40	20
	60	40	40	60	20	40	60	0	40	60	-20	40	60	-40	40
L=40	40	40	-40	40	20	-40	40	0	-40						
	40	40	-20	40	20	-20	40	0	-20						
	40	40	0	40	20	0	40	0	0	40	-20	0			
	40	40	20	40	20	20	40	0	20	40	-20	20			
	40	40	40	40	20	40	40	0	40	40	-20	40	40	-40	40
L=20	20	40	-40	20	20	-40									
	20	40	-20	20	20	-20									
	20	40	0	20	20	0	20	0	0						
	20	40	20	20	20	20	20	0	20						
							0	0	0						
							100	0	0						

Figure 3. 66 color chips from the CIELAB Gamut

Results and Analysis

The statistical analysis was conducted with IBM SPSS Statistics 16. The results are analyzed under two statistical analyses: descriptive statistics and inferential statistics (Chi-Square for Independence). 12 different surfaces of the dormitory room were given and university students were asked to fill every void area with one of the color choices from the given gamut. 12 surfaces were grouped into four sub-groups as architectural surfaces which compose of ceiling (n=191), wall (n=192) and floor (n=192); wood materials that compose of door (n=192), wardrobe (n=190), table (n=191), cabinet (n=190); fabric materials that compose of fabric of chair (n=189), bed sheet (n=180), pillow (n=185); and plastic as backside of chair (n=190).

The first group includes ceiling, wall and floor. The most preferred color for the ceiling is white coded as 100, 0, 0 (n=95) followed by light grey coded as 80, 0, 0 (n=24). University students prefer high lightness colors for ceiling in an order of 100 (n=95), 80 (n=69), 40 and 60 (both 40 and 60 selected in equal numbers n=12), 20 (n=2) and least in 0 (n=1). The least preferred values of a* and b* is where a* range is 40 (n=4) and -40 (n=8), and b* range is 40 (n=7) and -40 (n=4). Unlike preferences of ceiling, the most preferred wall color is light grey (80, 0, 0; n=34) followed by white (100, 0, 0; n=28). The preference of university students is more in the lightness of 80 (n=118) followed by 60 (n=28) and 100 (n=28), 40 (n=13), 0 (n=3) and least in 20 (n=2). From the combination of a* and b* values, 0, 0 is selected most by huge margin (n=75) without considering the L* which means that university students select achromatic colors more. Although the first and second most preferred wall colors are achromatic, the third and fourth most preferred colors are light blue (80, 0, -20; n=12) and light yellow (80, 0, 20; n=19). The preferred colors are overweighted in the region of achromatic colors. The most preferred color for floor is light grey 80, 0, 0 by 37 students similar with the wall color preference. The most preferred lightness is 80 for walls with a huge margin (n=96) followed by 60 (n=38), 40 (n=23), 20 (n=15), 100 (n=15) and 0 (n=5). The 0, 0 value of a* and b* for floor also overweighs the other combinations of a* and b*, which is also very similar with ceiling and wall color preference. The least preferred floor colors are highly saturated colors where a* is -40 (n=2) and b* is -40 (n=1). The pair of a* and b* zero is preferred more than the other pairs of a* and b*, which correspond to achromatic colors, followed by a* and b* values of 0 and 20 (yellow) respectively. In general, the light, achromatic and low saturated colors are preferred for surfaces of group one, namely ceiling, walls, floor.

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The second group surfaces which are materials, are selected mostly as wood materials in this dormitory room. The most preferred color is white 100, 0, 0 by 18 students followed by 16 students' preference of light yellow 80, 0, 20 for door and most preferred color of university students in terms of lightness is 80 (n=55), 40 (n=49), 60 (n=33), 20 (n=31), 100 (n=18) and 0 (n=6) consequently. The 0, 0 value of a* and b* is also selected most, very similar with the first group results; however, the values of 20, 20 (n=32) and 0, 20 (n=32) is followed after 0, 0 combination for door. Positive a* and b* correspond the angle of 0° and 90° with the hues of red (positive a*) and yellow (positive b*). These two-colors form different tones of orange stimuli in general and low lightness cause darker colors of orange. Thus, the door color is selected as brown, orange and yellow. The most preferred color is light yellow 80, 0, 20 (n=15) for wardrobe. The most preferred wardrobe color of university students, in terms of lightness is 80 (n=65), 60 (n=44), 40 (n=43), 20 (n=21) and 100 (n=12) and least in 0 (n=7). From the combination of a* and b* values 0, 0 (n=44) is preferred most followed by 20, 20 (n=29) for wardrobe. The preferred colors are overweighted in different areas where a* and b* are positive and L* value of 80, 60, 40 for wardrobe. The most preferred table color is light yellow 80, 0, 20 (n=27) and order of lightness is 80 (n=77), 40 (n=37), 60 (n=32), 100 (n=23) and 20 (n=19) and least in 0 (n=7). The 0, 0 values of a* and b* (n=52) is preferred most followed by 0, 20 (n=32). The most preferred cabinet color is yellow 80, 0, 40 (n=16). The order of lightness from most to least is 80 (n=68), 60 (n=47), 40 (n=41), 20 (n=22), 100 (n=8) and least in 0 (n=4). From the combination of a* and b* values 0, 0 (n=34) is most preferred. Moreover, the second and third most preferred colors belong to the area where b* is 20 but a* value is changing between 20 (n=25) to 0 (n=23). Thus, red and yellow hues are preferred more than blue and green hues which is very similar with wardrobe. The most preferred color is light yellow 80, 0, 20 (n=19) and second most preferred bed frame color is dark orange 60, 20, 40 (n=16). The order of lightness from most to least is 80 (n=58), 60 (n=48), 40 (n=40), 20 (n=21), 0 (n=12), 100 (n=8). Considering a* and b* pairs 0, 0 (n=37) values are preferred most for bed frame colors. The least preferred range belongs to where a* value is -40 (n=3) and only 3 student preferred colors from this range with b* values of 40 and L* is either 40 or 80. The preferred colors are overweighted in the areas where a* is 20 and 0, and b* values are 0, 20, 40.

The third group includes fabric of chair, pillow and bed sheet. The most preferred color of fabric is black 0, 0, 0 (n=20). The order of lightness from most to least is 80 (n=53), 40 (n=47), 60 (n=39), 20 (n=23), 0 (n=20), 100 (n=7). Although black is most preferred, the order of most preferred lightness shows that other colors from the range of L* 80, 40, 60 are also selected. When the combination of a* and b* values are considered 0, 0 (n=51) is most preferred. The least preferred range belongs to where a* value is -40 (n=2). The preferred colors are overweighted in the areas where a* and b* positive and a* is positive and b* is negative which corresponds as red, yellow and blue. Besides that, too many colors are preferred for sheet colors as almost all the colors from the given color gamut are almost preferred at least once by university students. The most preferred pillow color is white (n=63) and was selected more than twice as many as the second most preferred which is light grey (n=10) for pillow. The order of lightness from most to least is 100 (n=63), 80 (n=47), 60 (n=30), 40 (n=27), 20 (n=15), 0 (n=3). When the pairs of a* and b* values are considered 0, 0 (n=87) is most preferred. Thus, achromatic colors are preferred for pillow more than chromatic colors. The bed sheet lightness order from most to least 80 (n=59), 100 (n=57), 60 (n=29), 40 (n=20), 20 (n=12), 0 (n=3). Despite the fact that white 100, 0, 0 is the most preferred color, L* value of 100 is the second most preferred lightness. L* value of 80 is the highest preference lightness but colors in L* 80 range has more than one colors whereas L* 100 has only one color which is white. When the pairs of a* and b* values are considered 0, 0 (n=81) is most preferred. The least preferred range of a* and b* pairs belong to where a* is -40 and b* is either zero (n=4) or 20 (n=3). As a result, university students preferred almost hueless colors in pillows.

The final group includes only one surface: Backside of chair. The chair is plastic in real dormitory rooms. The most preferred color is black 0, 0, 0 (n=41). The order of lightness from most to least is 60 (n=43), 0 (n=41), 40 and 80 (n=35), 20 (n=31), 100 (n=5). Although black 0, 0, 0 is most preferred, L* equals to 60 have highest preference frequency. From the combination of a* and b* values 0, 0 (n=72) is most preferred. The least preferred range belongs to where a* values are -40 (n=4) nonetheless most preferred ranges are either a* (n=112) or b* (n=95) is zero. The preferred colors are overweighted in the areas where a* is positive and zero, no matter what the b* values are.

Overall, the most preferred color is white 100, 0, 0 for 4 different surfaces: ceiling, door, pillow and bed sheet. The most preferred color light yellow 80, 0, 20 is selected for wardrobe, table and bed frame. Light grey 80, 0, 0 is selected for the surfaces of wall and floor and yellow 80, 0, 40 is selected for only cabinet. These colors have a common property of high lightness values. Thus, university students preferred high lightness for all surfaces except two. Black 0, 0, 0 is the lowest lightness and most preferred in the area of backside and fabric of chair. The most preferred colors on all surfaces are shown in Figure 4.

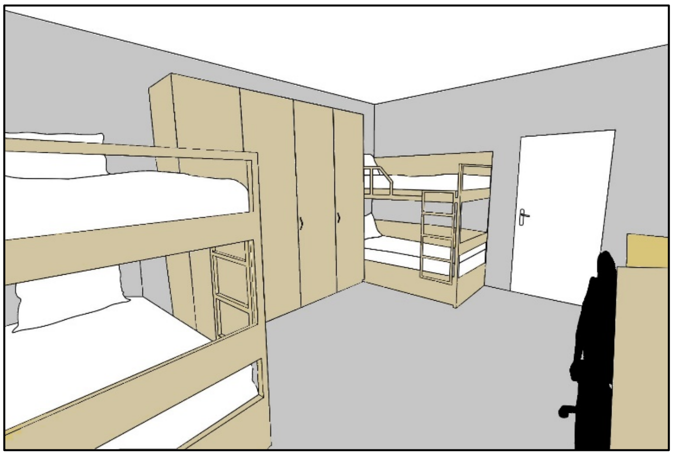

Figure 4. The most preferred colors depicted in two-dimensional line image of the dormitory.

The positive and negative values of a* and b* coincide with the saturated colors (red, blue, yellow and green), whereas the zero corresponds to achromatic colors. Positive b* (yellow) values with either 20 or 40 lightness are preferred in dormitory rooms. Thus, university students have a tendency to select yellowish colors more than other saturated colors. The difference between a* and b* indicate saturation level and it is concluded that low saturation is preferred for 11 surfaces except for the cabinet.

Chi-square test for independence was run for each surface to analyze the relationship between lightness and saturation. Two codes of L* values were eliminated from the calculation due to the system limiting their choices by design (black 0, 0, 0 and white 100, 0, 0). Eventually, there is no significant relationship between a* and b* values and preferences of university students for the cabinet (χ^2 (16) = 23.009, $p>0.05$). This implies an equal distribution of data among given values of L* for the cabinet but not for other surfaces. The direction and strength of correlation between lightness and saturation is decided by Pearson correlation separately for each surface. The direction of L* and a* have a negative correlation for all surfaces except for ceiling and backside of chair and L* and b* have a negative correlation for ceiling, door, floor, wardrobe and fabric of chair. Other surfaces (wall, table, cabinet, backside of chair, bed frame and pillow) show positive directional relation between lightness and saturation. The strength of association is very weak (negligible) between their respective L* and a* values for ceiling, wall, backside and fabric of chair whereas other

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surfaces have weak association. The strength of association between L* and b* values are very weak for all the surfaces provided. Overall, chroma and value were found to have a weak or very weak relationship with mostly negative correlation.

Conclusion

University students who accommodated at least one semester in a dormitory selected their preferred colors for 12 different surfaces of dormitory rooms. It is found out that high lightness and low saturation are preferred for almost all surfaces. A weak negative correlation between lightness and saturation is found. This study contributes to the literature mainly due to past color preference studies having been conducted regarding only some specific surfaces of interior spaces. Participants selected each surface one-by-one and color harmony preferences from real environment are avoided. Also, CIELAB is not commonly used in color preference studies but CIELAB is known to be the most scientific color system.

This study has some limitations due to the used methodology. The demographic factors such as age difference, past color education, culture, the level of familiarity to the place regarding how long the subjects have been accommodating in were similar among participants, so no comparisons in these regards were made. Also, the two-dimensional image shows only a part of the chosen dormitory type. Several other typologies are suggested to be investigated in future studies for both dormitories and various environments.

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Colour Meaning Matrix: A Tool for Connecting Concepts to Hue, Value and Saturation

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Abstract

In the ideation phases of any design process, designers usually establish conceptual parallels between the creative ideas of the project and colour as a visual language, through colour meaning and associations. However, translating abstract or textual concepts to colour selection can be very challenging when dealing with complex or sophisticated meaning associations without physical or concrete visual referents to relate to. At the same time, hue has traditionally been considered the most salient descriptor of colour and colour–meaning associations, as much of what is commonly termed the "psychology of colour" has organized emotional responses to colour, mainly through a hue paradigm. In recent years, several studies have demonstrated that value and saturation have particularly strong meaning connotations and consistent effects on emotions. While models of colour-concept association based on hue alone may work for single-colour applications, they do not lend themselves well to design contexts where multiple colours are used simultaneously, such as environmental design. The paper presents the Colour Meaning Matrix (CMM), a practical tool to guide the selection of colours to represent conceptual associations based on semantic polar differentiation. The tool provides guidelines and suggestions to relate concepts to the scales of hue, but most importantly, lightness and saturation for the colour-concept association, allowing designers to select colours that convey the intended emotional and contextual meanings. The Colour Meaning Matrix has been tested in didactic contexts of higher education in design, with more than 300 students in two countries in Europe and Latin America.

Keywords: colour meaning, colour design, colour psychology, semantic differentiation

Introduction – Research background

Colour is one of the fundamental elements in design to convey meaning and emotions. Since objects inherently display colours, and colours evoke emotional responses that influence daily life, their semantic associations hold significant importance. A large number of studies point to connections between colour, meaning and emotion (e.g., Adams and Osgood, 1973; Byrnes, 1983; Kreitler and Kreitler, 1972; Schaie, 1962; Wexner, 1954). For instance, the impact of colour on emotions and preferences plays a crucial role in visual communication and marketing (Singh, 2006), and the colours of products can shape consumers' attitudes, either positively or negatively, and are instrumental in distinguishing products, brands, and corporate identities. The evocative and communicative nature of colour is not only related to personal intuition or experience. The chromatic aspect that characterises an image, a product or object or an environment can be articulated by the designer to stimulate perceptual and emotional responses in individuals, affecting their behaviour (Kotler, 1973). Colour can be used to visually communicate a specific mood. At the same time, colours can generate a psychological response in the observer: they may be identified as “mood colours,” such as bright colours tend to cheer people, or neutral can be chosen to produce calm. Significance also influences our perception of colour and the function of designed objects; the meanings and use of colour may evolve from significant or cultural events and change based upon context (DeLong and Martinson

2012). Colours can represent a nation or institution, a group of people, a product, or an idea, and they can also symbolize and communicate social position.

- The hue paradigm: the traditional viewpoint

The emotional and semantic associations of colour have been commonly nominated with the name "colour psychology" or "colour meaning", and its study for decades has mainly focused on the effects of hue (i.e., the attribute of a colour dependent on its dominant wavelength and independent of intensity or lightness, the most prominent quality by which we distinguish one colour from another) as the salient colour emotion descriptor. This approach has been described as the *"hue paradigm"*. People frequently associate certain emotions with particular hues (the subjective experience of anger is usually associated with the concrete concept of red because red correlates with the bodily experience (i.e., sensory, physiological) of increased blood flow during the experience of anger (Drummond and Quah, 2001). This approach has been largely studied: numerous research in the last century have investigated colour meaning only by inquiring on hue associations, without taking into account the other two attributes of colour, namely lightness and saturation. To approach the semantic aspects of colour taking into consideration only the aspects related to hue presupposes two significantly critical aspects: (i) the **plurality of meanings of a same hue,** and (ii) the **cultural-sensitive dichotomy.**

Firstly, the *plurality of meaning of the same hue* is pretty self-explanatory. Several research studies have found contradictory results (including antonymous concepts) for the meanings of the same hue. Moreover, some colours may be associated with several different emotions and some emotions are associated with more than one colour (Linton, 1999; Saito, 1996). When examining the meanings of red, for instance, this hue evoked a range of emotional associations—from negative connotations (such as danger) in achievement-related contexts to positive connotations (such as sexual readiness) in relational settings (Elliot and Niesta, 2008). Additionally, red was associated with both happy and angry faces (Palmer *et al.,* 2013). Furthermore, red was seen to be positive because it was associated with love and romance, while the negative aspects of red included having associations with fight and blood as well as Satan and evil (Naya and Epps, 2004). On other examples, blue was generally rated very positively (Adams & Osgood, 1973; Valdez and Mehrabian, 1994), yet it was linked to both calm and sad faces (Palmer *et al.,* 2013). Yellow was commonly paired with happy faces and upbeat music (*ibid*.), but when lightness and saturation were controlled, it was rated as the least pleasant colour in Valdez and Mehrabian's (1994) study. This plurality of colour meanings for the same hue has also been widely disseminated, including through literature, which has given rise to several misconceptions among the general public. But it raises more questions than it helps to answer: *How can the same hue be positive and negative at the same time or how can it simultaneously mean happiness and sadness, love and evil? What is its real meaning then? Do these pluralities of meaning help designers make colour decisions or do they confuse them?*

The other critical aspect of the hue paradigm is the *cultural-sensitive dichotomy*. This dichotomy proposes that on the one hand, in diverse cultures, different meanings are attributed to colour, according to the perceptions of value and local meanings of the territories or cultural affiliations. Therefore, colour conventions differ from one society to another. A well-known example is the two achromatic colours, black and white. Death and mourning are associated with the colour black in Western traditions, whereas in China the colour of death is white. Black can be associated not only with royalty, power, and wealth, but with death, mourning, and tragic events (Naya and Epps, 2004). Also in Asia, orange is a positive, spiritually enlightened, and life-affirming colour, whereas, in the United States, it is a colour of road hazards, traffic delays, and fast-food restaurants. However, different studies have concluded that the influence of cultural background on colour emotion and meaning association is very limited (Gao and Xin, 2006). A good cross-culture consistency for the emotional connotation of colours was observed when comparing the results obtained in studies conducted in Sweden, Greece and Japan (*ibid*). Osgood studied anthropological field reports on five widely separated primitive cultures – Aztec and Pueblo Indian, Australian Bushman, Siberian Aborigine, Black (Uganda Protectorate) and Malayan – to obtain evidence on semantic parallelism. The generality of certain relationships was quite striking (Osgood *et al.,* 1967). Moreover, emotions were associated with colours similarly for US college students, Tzeltal-speaking people in Chiapas and Arawakan speaking Machiguenga in Peru. The dichotomy relies then on the fact that many (hue-based) colour–emotion associations vary between cultures while others appear consistently from one culture to the next. Both aspects of the dichotomy are contrasted when on the one hand, colour is undoubtedly, from an anthropological and ethnographic point of view, a powerful symbolic instrument that allows the differentiation and identification of cultures, but from a psychological perspective, there seems to be a human corporal and universal response to the stimulus of colours. So other questions arise: *Is colour meaning something agreed upon or is it inherent to human nature, such as a subconscious language? When designing colour, should we consider context-based meanings or universal, cross-cultural meanings?*

- <u>More than hue: the contemporary approach</u>

Due to the criticism that the "hue paradigm" has aroused as illustrated above, in recent years the study of the colour meaning and emotional associations has started to highlight the value and importance of the other two colour attributes: lightness (i.e. the light that a colour reflects, the attribute of colour consisting of a scale between black and white, how light or dark the colour is) and saturation (i.e. the intensity or purity of a hue, the extent of its colourfulness, and the strength or richness of a colour, indicating whether it is vivid or dull). Furthermore, different studies suggest that saturation and lightness are more important for the effects of colours on emotions than hue (Gao and Xin, 2006; Solli and Lenz, 2011). In 1994, Valdez and Mehrabian showed that changes in value (lightness) and chroma (saturation) can alter the emotional significance of a colour. In their study, they explored how participants responded to hue, lightness and saturation using the Pleasure-Arousal-Dominance (PAD) model. Their findings revealed that saturation had a significant and consistent impact on emotions being typically linked to Arousal, and lightness as associated with Dominance. Pleasure was connected to colours with both higher lightness and greater saturation (Valdez & Mehrabian, 1994).

Concerning the importance of lightness, Wright and Rainwater (1962) found that participants rated lighter colours more often using adjectives relating to happiness (happy, young, social, etc.). Valdez and Mehrabian (1994) showed also that people rated lighter chromatic and achromatic colours more positively. Similarly, Hemphill (1996) reported that viewing lighter colours elicited associations to positive affective states (e.g., white, pink, yellow, etc., associated with happiness and positivity) while viewing darker colours mainly produced associations to negative affective states (e.g. grey with sadness and boredom). Additionally, in a study by Adams and Osgood (1973), individuals from 23 cultures rated eight colour terms denoting higher lightness (white as compared to grey, as compared to black) as higher in pleasantness; while higher darkness (black) was the most consistently agreed upon colour concept as far as affect was concerned, finding it very bad, very strong and very passive (p. 147).

In addition to lightness, saturation might be more important in determining other affective associations, such as those with arousal or potency. Colours related to bodily expressions of positive (joy) emotion would have an overall higher lightness and saturation value than would colours chosen to go best with negative (fear) emotion (Dael *et al.*, 2016). Saturation has a more important role in determining the intensity of affective associations, such as those with arousal or potency, and it also seems to have some consistent influence on average active/passive colour judgements. For Dael *et al.* (*ibid*), all three colour attributes are likely to be important when processing affective nonverbal person information, though not independently from each other. Related to this, Wright and Rainwater (1962) found that some meanings or associations hardly depend on hue, but in a combination of lightness and saturation of the specific colour. Some examples of this are the concept of “happiness”, which usually means an increase in lightness of a colour, and where saturation also makes a substantial contribution to it. Thus, the lighter or the more saturated the colour, the more “happiness” it connotes. Or the concept of “showiness”, which depends on lightness and saturation, but with a different emphasis: it is closely related to a high saturation. Interesting is the case of “forcefulness”, which can be affected by lightness and saturation distinctly: the darkest colour is, the strongest, but at the same time, a saturated colour is perceived as strong; high darkness and high saturation are not compatible in colour appearance: they can exist only apart from each other.

- Colour meaning decisions in the conceptual phase of design

In the ideation phases of any design process, designers usually establish conceptual parallels between the creative ideas of the project and colour as a visual language, through colour meaning associations. However, the prevailing model in much of the literature and resources available online on colour meaning for design is still the “hue paradigm”, which is not very useful for designers to tackle colour meaning challenges in real projects. In addition to the criticisms proposed above, Divers (2023) provides two other reasons for the need to abandon the “hue paradigm” in design practice and to embrace a perspective that considers the other two colour attributes: first, research findings have limited practical application because colours are usually studied individually, in isolation, to control the effects of colour interaction. However, designers are primarily tasked with managing the interplay of multiple colours, making this focus on single colours less relevant to their work; second, generalizations about hues typically refer to their full-saturation versions; for instance, red can be "exciting" in its most vivid form but tends to lose that effect when presented in muted, pale, or darker shades. Interestingly, designers tend to use muted colours more often than vibrant ones, which means research in this area often offers little practical guidance.

All of the above stresses the fact that designers **need practical tools and resources that may help them to make decisions related to colour meaning for real projects.** These tools must be updated and consider state-of-the-art knowledge, the contemporary approach to colour meaning beyond the “hue paradigm”. Some considerations to colour synaesthesia (i.e. the condition in which stimulation in one sensory or cognitive stream involuntarily, or automatically, leads to associated internal or external experiences in a second unstimulated sensory or cognitive system) can be helpful in the case of projects that may stimulate sensitive responses on users (such as the evocation through colour of the senses of taste, touch or smell in the case of some packaging projects, or the relation of colour with sound in projects related to music, among others). Another way to go is reviewing the contemporary aspects of colour associations concerning the final product's contextual, emotional, and cultural variables. These actions are usually supported by creating mood boards and working with design tools that may help translate abstract features of the creative concept into more concrete formal aspects or design elements.

Methodology

- The semantic differential method (SD)

Studies on colour emotion and meaning associations (several from the ones cited above) have usually examined colour meaning indirectly with the aid of psychological scales, such as the semantic

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differential (SD) method, developed by Osgood et al. (Osgood *et al.,* 1967) for the analysis of meaning and is particularly useful to assess subjective judgments and attitudes. The SD is a psychological scaling method developed to understand how people perceive the meaning of words and concepts. Instead of asking individuals to describe the meaning of a word, they are asked to rate it on a series of bipolar adjective scales (e.g., *good-bad*, *strong-weak*, *active-passive*). The notion of using polar adjectives to define the termini of semantic dimensions grew out of research on synaesthesia during the first part of the XX century. Interrelationships among colour, mood, and musical experiences were studied, where subjects were asked first to relate music to a mood circle, and then, to select appropriate colours for those moods, resulting in consistent relations (*ibid,* pp.20-21). From those studies, the imagery found in synaesthesia was intimately tied up with language metaphor, and both of them represented semantic relations. The colour-music synaesthesia could then be described as the parallel alignment of two or more dimensions of experience, definable verbally by pairs of polar adjectives (*ibid,* p. 23).

When the SD method is used to assess colour meaning, usually, each bipolar scale is defined by a pair of polar (opposite-in-meaning) adjectives (e.g., joyful, sad, hard or soft), and the subject judges how a given colour is more related to one of the other pole of the scale. Each judgment reflects a choice and helps position the concept as a point within the semantic scale (from left to right). The more scales used, and the more representative those scales are, the more accurately this point reflects the operational meaning of the concept. The difference in meaning between two colours depends on the difference in how they are positioned within a shared scale (e.g., hot __ __ X __ __ __ __ cold). Osgood et al. (1967) also discovered that people's ratings consistently boiled down to *three core dimensions of meaning,* which he referred to as:

a. <u>Evaluation,</u> whether something is good or bad, desirable or undesirable.
b. <u>Potency,</u> how strong, powerful, or weak something is.
c. <u>Activity,</u> whether something is active, dynamic, or passive.

In a nutshell, the overall results of applying SD scales for assessing colour demonstrate that the *evaluation dimension* is strongly associated with lightness, while *potency* tends to go with higher darkness and high saturation. *Activity* is most strongly associated with saturation, but also with brightness, where white is more active than both grey and black. The SD method usually demonstrates that colour emotion and meaning connotations are mainly connected to lightness and saturation, and less connected with hue (Adams and Osgood, 1973).

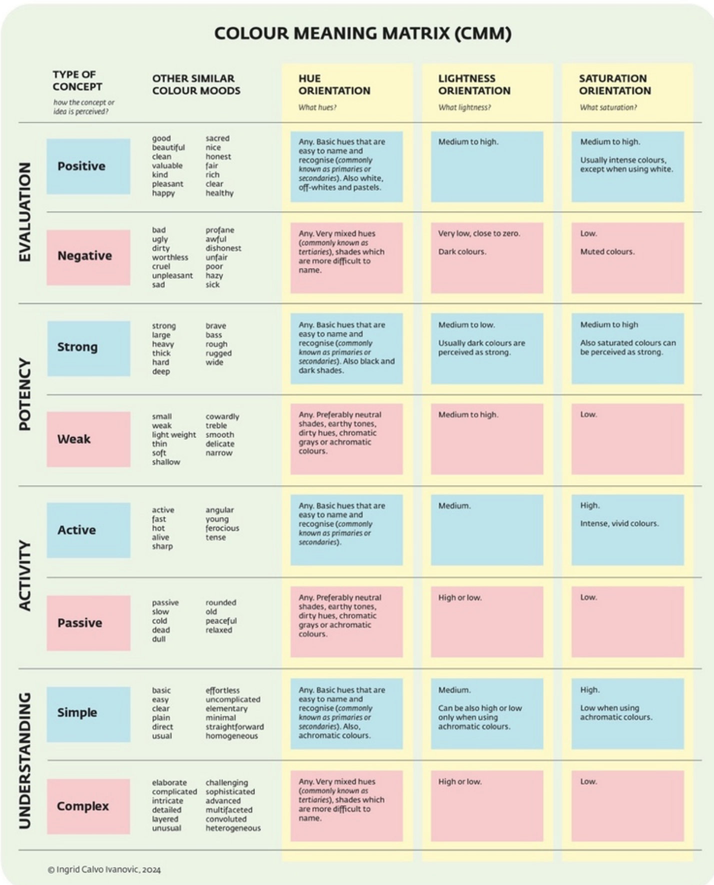
- <u>Application of the SD method with design students</u>

A set of exercises for the construction of semantic colour palettes, that is, colours chosen according to their meaning, were carried out with students of the *"*Colour Application*"* course of the third year of the Design program and the Arts and Crafts program at two Chilean universities. Additionally, exercises were carried out within the "Colour" teaching module with students in the first year of the Product Design program at an Italian university. All the exercises were carried out from 2021-2024, with more than 300 students.

Starting from a colour-music synaesthesia exercise, each student was given two pieces of popular instrumental music, with different moods (one joyful, other calm). The assignment was (*step 1*) to listen to the music and to write down concepts, words, feelings or ideas that were evoked by the musical mood for each piece. In parallel, (*step 2*) the students had to create 2 colour palettes, of ten colours each, that represented the mood of each music piece listened (one for each song). Subsequently, (*step 3*) students had to choose the most representative word or concept for each song (resulting in 2 words in total) and create a new composed concept with both words (e.g. by using the words "movement" and "disconnection", a student could create the concept of *"disconnected movement"*), and (*step 4*) compare both words to four given bipolar scales for semantic differentiation: the 3 original Osgood's dimensions of meaning, namely, the *evaluation scale* (positive/negative), the *potency scale* (strong/weak), and the *activity scale* (active/passive); and a fourth novel scale proposed by the researcher, called the *understanding scale* (simple/complex). The SD was used for facilitating the students' comprehension of the semantic mood of each concept and therefore, define their colour moods. Finally, with this judgement, (*step 5*) definitive 5-colours palettes were created, from the conceptual and colour moods defined, by using five colours from among the ones chosen in step 2. The application of this exercise after four years resulted in the creation of more than 1000 colour palettes (an average of 3,5 palettes per student), and around 350 composed concepts that were evaluated with the SD method. During this experience, collective discussions and different analyses were made throughout the years with the students, to understand what the colour appearance and therefore the attributes of the colours, were for each polarity. Some of the questions posed were: *How is the lightness of concepts with positive meanings? How is the saturation of colours related to active meanings? How are the colour attributes of a complex concept? What hues represent better the concept of strong or weak?* The answers to these and many other questions were obtained from the visual evidence, namely, the colour palettes created by the students and their comparison.

Results: The Colour Meaning Matrix (CMM)

From the collective analysis and discussion, the creation of the Colour Meaning Matrix (CMM) was proposed, as a practical tool to guide the selection of colours to represent conceptual associations based on semantic polar differentiation. The tool provides guidelines and suggestions to relate ideas



COLOUR MEANING MATRIX (CMM)

	TYPE OF CONCEPT *how the concept or idea is perceived?*	OTHER SIMILAR COLOUR MOODS	HUE ORIENTATION *What hues?*	LIGHTNESS ORIENTATION *What lightness?*	SATURATION ORIENTATION *What saturation?*
EVALUATION	Positive	good, beautiful, clean, valuable, kind, pleasant, happy, sacred, nice, honest, fair, rich, clear, healthy	Any. Basic hues that are easy to name and recognise (*commonly known as primaries or secondaries*). Also white, off-whites and pastels.	Medium to high.	Medium to high. Usually intense colours, except when using white.
	Negative	bad, ugly, dirty, worthless, cruel, unpleasant, sad, profane, awful, dishonest, unfair, poor, hazy, sick	Any. Very mixed hues (*commonly known as tertiaries*), shades which are more difficult to name.	Very low, close to zero. Dark colours.	Low. Muted colours.
POTENCY	Strong	strong, large, heavy, thick, hard, deep, brave, bass, rough, rugged, wide	Any. Basic hues that are easy to name and recognise (*commonly known as primaries or secondaries*). Also black and dark shades.	Medium to low. Usually dark colours are perceived as strong.	Medium to high. Also saturated colours can be perceived as strong.
	Weak	small, weak, light weight, thin, soft, shallow, cowardly, treble, smooth, delicate, narrow	Any. Preferably neutral shades, earthy tones, dirty hues, chromatic grays or achromatic colours.	Medium to high.	Low.
ACTIVITY	Active	active, fast, hot, alive, sharp, angular, young, ferocious, tense	Any. Basic hues that are easy to name and recognise (*commonly known as primaries or secondaries*).	Medium.	High. Intense, vivid colours.
	Passive	passive, slow, cold, dead, dull, rounded, old, peaceful, relaxed	Any. Preferably neutral shades, earthy tones, dirty hues, chromatic grays or achromatic colours.	High or low.	Low.
UNDERSTANDING	Simple	basic, easy, clear, plain, direct, usual, effortless, uncomplicated, elementary, minimal, straightforward, homogeneous	Any. Basic hues that are easy to name and recognise (*commonly known as primaries or secondaries*). Also, achromatic colours.	Medium. Can be also high or low only when using achromatic colours.	High. Low when using achromatic colours.
	Complex	elaborate, complicated, intricate, detailed, layered, unusual, challenging, sophisticated, advanced, multifaceted, convoluted, heterogeneous	Any. Very mixed hues (*commonly known as tertiaries*), shades which are more difficult to name.	High or low.	Low.

Figure 17: The Colour Meaning Matrix

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to the scales of hue, but most importantly, lightness and saturation for the colour-concept association, allowing designers to select colours that convey the intended emotional and contextual meanings. The CMM is structured horizontally in eight rows: four dimensions of meaning with two poles each i.e., “evaluation” (positive and negative poles), “potency” (strong and weak poles), “activity” (active and passive poles), and “understanding” (simple and complex poles). Vertically, the CMM is structured in five columns, corresponding to: “type of concept” (how the concept or idea is usually perceived?), “other similar colour moods” (synonyms that can be used), “hue orientation” (what hues to select?), “lightness orientation” (what lightness to select?) and “saturation orientation” (what saturation to select?) (Fig. 1). The orientations included in the CMM are the result of the big amount of data collected, years of observation and the collective discussions indicated above.

The matrix is a tool for inquiring the semantic visual representation of the concepts or creative ideas, and it is meant to be used when the designer already has defined a concept for a project, by assessing it about the four different dimensions of meaning, e.g. starting from the first meaning dimension one could ask: *is my concept usually perceived as positive?*, if the answer to this question is *yes*, then the “positive” (row 1) orientations for hue, lightness and saturation may be followed as suggestions to choose colours with a that mood or character. If the answer to the same question instead is *no*, then it may mean that the concept is usually perceived as negative, and then the user may follow the orientations for the “negative” colour mood (row 2). But the answer to the question could be also *not applicable*, as not all ideas may be classified or judged as “positive” or “negative”, there are also some neutral concepts in terms of good or bad. If this is the case, the user of the CMM may proceed to evaluate her concept with the second meaning dimension, hence, “potency” and the second pair of polarities (rows 3 and 4) of strong and weak. Then, the logic of questions and answers is the same, until the concept or idea has been compared to all four meaning dimensions.

Conclusions

Since 2022, previous and partial versions of the CMM that is presented in this article were tested with students, which has led to the continuous improvement of the current tool. During the last three years, the CMM has been demonstrated to be useful for design students and professionals as it facilitates the process of colour decision-making, in terms of semantic associations. The CMM was not intended to be used as a formula, but as an orientation for the chromatic choices, and for this reason, it should not be conceived only as an answer but as a starting point for the semantic exploration of colour. The criteria and contents of the CMM are based on the evidence obtained from the literature review of the cited literature and others, on experimentation and four years of development of the tool from a large amount of analysed data, reflections and visual research through chromatic palettes. Future and ongoing developments consider the intersection of semantic dimensions and their polarities in a three-dimensional space, as well as an addendum or twin of the matrix created by incorporating synesthetic categories such as: wet/dry, tasty/insipid, rumorous/silent, among others.

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Between the lines: a survey to evaluate how light color gradients affect emotions

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Abstract

This article explores the hypothesis that light, through different color gradients within it, can influence individuals' moods and emotions while doing simple operations like reading a text. This premise is rooted in the theory of color psychology, which suggests that colors can evoke certain emotions and behaviors. Light, being a spectrum of colors, may thus have the potential to influence mood and emotions, particularly during reading when the reader's engagement is high and they are more susceptible to subtle environmental cues. To test this hypothesis, this study employs a series of psychological questionnaires designed to measure participants' emotions, arousal, and anxiety levels. These questionnaires are administered after exposure to different lighting conditions, with varying brightness levels, CCTs, and color gradients. The aim is to establish a correlation between the lighting conditions and the emotional and behavioral responses of the participants. The research builds on previous studies that have demonstrated the influence of light on mood and cognitive performance. Küller (Küller *et al.*, 2006) found that light quality affects employees' mood and well-being in work environments. Knez (Knez, 2001) highlighted how different color temperatures of light can influence cognitive performance and mood. Recent research (Bortolotti *et al.*, 2022) has delved deeper into the influence of perceived color lightness on psychological functions. This research investigates how the perception of color lightness can affect various psychological processes, adding another layer to our understanding of the complex relationship between light, color, and human psychology. The study examines how light, particularly its color and intensity, can influence mood and emotions through its impact on circadian rhythms and the production of hormones such as melatonin and serotonin. Many researches have shown that intrinsically photosensitive retinal ganglion cells (ipRGCs) play a crucial role in this interaction, influencing circadian rhythms and acute behavioral responses to light. As a premise for this research, we have raised the question of whether colour and light affect physiology and psychology in proportional ways. Our research suggests a complex interplay between the physical properties of light and colour and their psychological and physiological effects, highlighting the need for a nuanced understanding of these relationships. The findings of this study could have implications for various fields; optimizing lighting conditions in education and office settings could enhance reading comprehension and productivity. In conclusion, this article presents a comprehensive investigation into the potential influence of light, through its color gradients, on individuals' moods and emotions during text reading. Integrating psychological measures with exploring physiological mechanisms provides a thorough and credible understanding of this phenomenon.

Keywords: Color, Light, Design, Emotion, Behaviour.

Introduction

Human perception of the physical world is predominantly visual. Despite extensive research on the nature of light and vision, the design of lighting for individual well-being is a relatively recent discipline. Historically, lighting design focused on optimal illumination levels for productivity and energy efficiency. However, scientific evidence from the 1990s onwards has highlighted the significant role of light and color in influencing human well-being and performance (Cajochen *et al.*, 2005).

The phenomenon of vision has been studied since the fifth century BC, but it is only in modern times that we have achieved a satisfactory description of the nature of light and how our visual system interprets it. For decades, the primary concern of designers was to ensure optimal lighting levels for workers, passersby, or tourists, with attention to energy savings where possible. The scientific proof that light and color actively contribute to well-being and performance had to wait until the 1990s to be considered at a production level. Laws and standards have traditionally focused on the quantitative aspects of light and only recently have begun to include the psycho-physiological well-being of humans. Recent advancements in human-centric lighting have further emphasized the importance of considering both visual and non-visual effects of light. Human-centric lighting aims to support human health, well-being, and performance by mimicking natural light patterns and adjusting artificial lighting to align with human circadian rhythms (Houser et al., 2021). This approach recognizes that light influences not only vision but also various biological processes, including sleep, mood, and cognitive function (Jalali *et al.*, 2024) among others. The impact of light on human physiology is mediated through specific retinal structures known as Intrinsically Photosensitive Retinal Ganglion Cells (IPRGCs), which contain the photosensitive protein melanopsin. These cells play a crucial role in regulating the circadian rhythm by influencing the production of melatonin, a hormone that governs the sleep-wake cycle (Hattar *et al.*, 2002). The suppression of melatonin by light exposure, particularly blue light, has been well-documented and is a key factor in designing lighting systems that support healthy sleep patterns (Brainard *et al.*, 2001). Moreover, the psychological effects of light and color are equally significant. Studies have shown that different colors can evoke various emotional responses and influence mood and behavior. For instance, warm colors like red and yellow are often associated with feelings of warmth and excitement, while cool colors like blue and green are linked to calmness and relaxation (Boyce, 2014). The integration of these psychological insights into lighting design can enhance the overall well-being and productivity of individuals in various environments, from workplaces to healthcare facilities. The design of lighting systems that consider both the physiological and psychological effects of light and color is essential for promoting human well-being. By understanding the complex interplay between light, color, and human responses, we can develop lighting solutions that not only meet functional requirements but also enhance the quality of life.

Literature Review

Light affects human physiology through mechanisms distinct from vision. Specific retinal structures, Intrinsically Photosensitive Retinal Ganglion Cells (IPRGCs), contain melanopsin, a photosensitive protein that influences the circadian rhythm by suppressing melatonin production (Hattar *et al.*, 2002). This physiological response differs from the psychological perception of color, which is processed in the cerebral cortex (Thapan, Arendt and Skene, 2001). The relationship between light and human physiology has been thoroughly investigated. IPRGCs, which contain melanopsin, perform phototransduction similarly to other photoreceptors like cones and rods. However, the electrical impulse created by these cells follows a different path from vision, being conveyed through the retina-hypothalamus tract to influence the pineal gland and suppress melatonin. This hormone is crucial in regulating the human circadian cycle (Hattar *et al.*, 2002).

These studies highlight a fundamental aspect, light influences humans physiologically through mechanisms that differ significantly from those of vision, except for the initial segment in the eye. In vision, after phototransduction by cones and rods, the electrical signal is sent to the optic nerve towards the cerebral cortex, where the psychological sensation of color is formed. This difference is also evident in human sensitivity to different wavelengths of light (different colors). In the spectral sensitivity curve (which colors we see best), the maximum response coincides with 555 nm (yellow-green), while in the sensitivity curve concerning the circadian cycle, the maximum sensitivity corresponds to 460 nm (blue) (Thapan, Arendt and Skene, 2001). The differences between these two mechanisms are reflected in human color perception. It is not uncommon for an individual to associate the term "activating" with warm and vibrant colors like yellow and red, while physiologically speaking, activating colors are at the opposite end of the spectrum (blue). Is it possible that the psychological interpretation we give to colors is so different from the one that influences our physiology? Considering a holistic approach, a complex organism like ours should find at least some points of convergence between these two mechanisms. Unfortunately, studies on the psychology of colors often lack the methodological and scientific rigor typical of those on physiology, and although there is a vast bibliography, it is challenging to extrapolate assumptions suggesting a proportional relationship between the two mechanisms. Recent research has expanded our understanding of how light affects human physiology beyond the visual system. For instance, studies have shown that exposure to blue light can significantly impact alertness and cognitive performance, which is particularly relevant in designing lighting for work environments (Cajochen *et al.*, 2005). Additionally, the role of light in regulating mood and emotional states has been explored, with findings indicating that light exposure can influence the production of serotonin, a neurotransmitter associated with mood regulation (Lambert *et al.*, 2002). The psychological effects of light and color are equally significant. Studies have shown that different colors can evoke various emotional responses and influence mood and behavior. The integration of these psychological insights into lighting design can enhance the overall well-being and productivity of individuals in various environments, from workplaces to healthcare facilities.

After an extensive research phase (Siniscalco, Bortolotti and Rossi, 2022) and an analysis of the issue typical of psychological research (Siniscalco and Bortolotti, 2023), we designed a test whose primary objective of this study is to evaluate whether colored light has psychological effects that are proportional to all evaluated subjects. Researchers hypothesize that psychological responses to colored light may differ from physiological responses. This finding could lead to new awareness when implementing specific applications of colored light to mitigate psycho-emotional discomfort in Human-Centric lighting designs. By understanding the complex interplay between light, color, and human responses, we can develop lighting solutions that not only meet functional requirements but also enhance the quality of life.

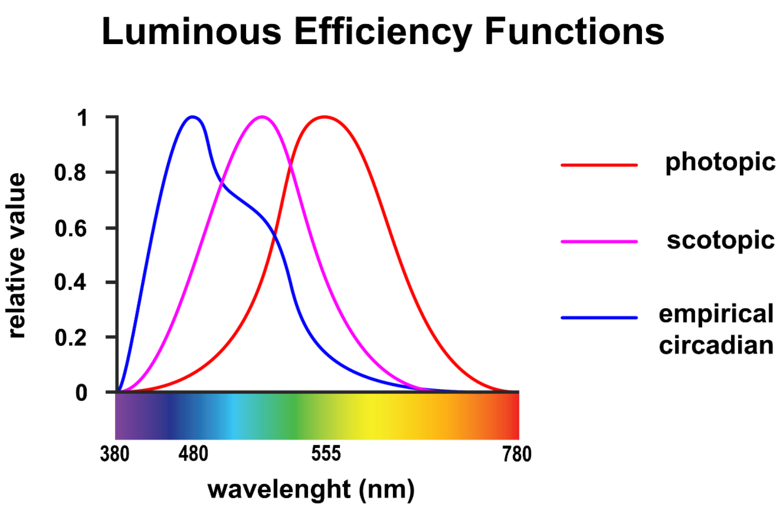

Fig. 1 - The three curves represent the efficiency of light in different aspects. The photopic curve is the human sensibility to color in normal lighting conditions. The scotopic curve is the sensibility to color in very dim light conditions. The empiric circadian curve (derived from the studies of Brainard and Thapan) shows the sensibility to the spectrum of our organism in relation to the physiological reaction to light. While the first two curves are based on vision (thus implying the involvement of the meaning of what the subjects are seeing and interpreting), the last curve is unrelated to vision and describes the efficiency of suppressing Melatonin (sleep hormone) without the involvement of information elaboration by the brain.

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Test design

The test aimed to verify the psychological response of the subjects under different conditions of colored lighting. The setup of the experiment involves reading a text that is not related to the test but that requires concentrated reading. The text (an excerpt from a specialized magazine) has been selected so as not to arouse particular emotional reactions. The subjects were in a classroom, and their positions were placed in front of a wall 220 cm away, which served as a secondary light source. The table on which the text to be read was present was illuminated by the direct light of a "tunable white" luminaire (obtained with LEDs converted by phosphors) placed perpendicular to the surface at a distance of 220 cm. This luminaire was able to produce a range of color temperatures from warm (2700 K) to cool (6500 K) and a surface illuminance of 340 lux for warm light and 452 lux for cold light. In addition to the "tunable white" light, the system included a Formalighting Galileo 390 projector, placed behind the subjects, capable of illuminating the wall in front of them with colored light obtained through the mix of RGB LED sources. The positioning of the light sources was designed to provide a predominantly white light on the task and a colored light peripherally in the field of view. The light intensities have been empirically modulated in order to compensate for the different efficiencies of the lighting sources, ensuring natural lighting on the task but an appreciable chromaticity in the peripheral area of the visual field (Figure 2).

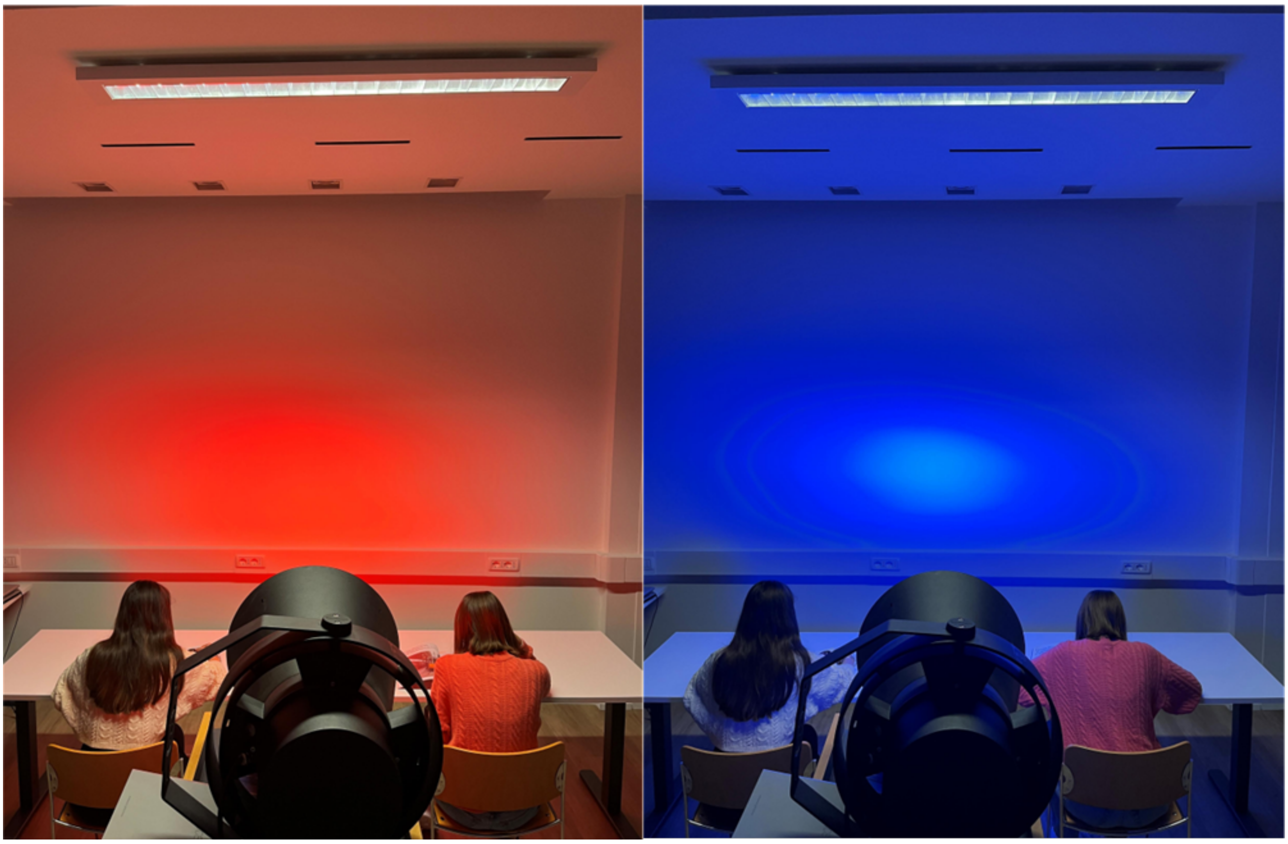

Fig. 2 - Two subjects read the assigned text in two different lighting conditions. On the left, we have a white light at 2700K and a red light, while on the right, we still have the white source at 2700K but combined with a blue light.

The test was administered to groups of two participants at a time, who were engaged in the reading activity for ten minutes. The test was divided into two five-minute sessions, interspersed with a two-minute break during which the subjects were prohibited from using electronic devices. Each session involved exposure to a light scenario for 145 seconds, followed by another scenario of the same duration. The transition between the two lasted 10 seconds. The lighting scenarios included tunable

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white light and colored light, except for one control scenario, which contained only tunable white light. The scenarios are represented in Figure 3.

01A	145s	10s	145s
from	Warm white	to	Cool White
from	Red	to	Blue
on surface	233 lux		204 lux

01B	145s	10s	145s
from	Cool White	to	Warm white
from	Red	to	Blue
on surface	186 lux		201 lux

04A	145s	10s	145s
from	Warm white	to	Cool White
from	Green	to	Magenta
on surface	217 lux		216 lux

04B	145s	10s	145s
from	Cool White	to	Warm white
from	Green	to	Magenta
on surface	213 lux		213 lux

02A	145s	10s	145s
from	Cool White	to	Warm white
from	Blue	to	Red
on surface	204 lux		233 lux

02B	145s	10s	145s
from	Warm white	to	Cool White
from	Blue	to	Red
on surface	201 lux		186 lux

05A	145s	10s	145s
from	Cool White	to	Warm white
from	Magenta	to	Green
on surface	216 lux		217 lux

05B	145s	10s	145s
from	Warm white	to	Cool White
from	Magenta	to	Green
on surface	213 lux		213 lux

03A	145s	10s	145s
from	Cool White	to	Cool White
from	Blue	to	Red
on surface	204 lux		186 lux

03B	145s	10s	145s
from	Warm white	to	Warm white
from	Red	to	Blue
on surface	233 lux		201 lux

CONTROL A	145s	10s	145s
from	Warm white	to	Cool White
on surface	340 lux		452 lux

CONTROL B	145s	10s	145s
from	Cool White	to	Warm white
on surface	452 lux		340 lux

Fig. 3 - Diagram that reproduces the lighting scenarios used during the test. The first three groups were chosen to depict chromatic changes to stimulate the transition from a "warm" to a "cold" environment. Groups 4 and 5, on the other hand, used colors that, on the CIE 1931 chromaticity diagram, have an orientation perpendicular to the one used in the first three groups. Finally, the control group was used to observe whether even the correlated color temperature alone was able to highlight a clear preference in the subjects.

This test presents the first phase of the research's investigation. Therefore, no personal data were collected on the subjects except that they were all males and females between 18 and 25 years old. Normal color vision was required to participate in the test.

Forty-eight subjects took part in the test: ten for each of scenes 1, 2, and 3; six for each of scenes 4 and 5; and six for the control groups.

The first three setups were designed to understand how subjects responded emotionally to light gradients that ranged sharply from a "perception of a warm atmosphere" (warm white and red) to a "perception of a cold atmosphere" (cold white and blue). Then, we tried to cross the various elements (from cold white and red to warm white and blue) to understand if the subjects had a much clearer response to that of the previous scene. Other combinations were also tried, and even two different colors (green and magenta) were used to understand if they were able to bring out clear preferences, such as scenarios with colors more related to the perception of a hypothetical "environmental temperature."

At the end of the exposure to light, each person was subjected to a structured interview that contained general questions about their sleep quality, their routine related to exposure to artificial light, and their awareness of the influence of light on their biology.

Finally, the questionnaire asked about evaluating the light gradient during the tests. The subjects had to indicate whether they perceived an improvement or worsening in the quality of light.

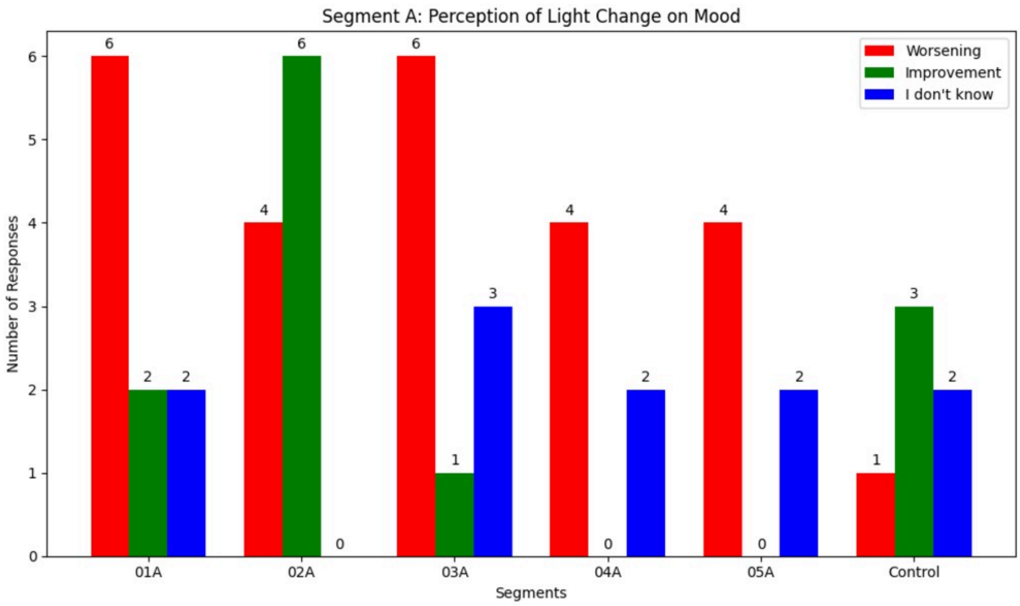
Results

The majority (98%) of respondents stated that they are aware that light can change their mood and their ability to concentrate (96%). To avoid any bias in providing answers to the questionnaire, the subjects were not made aware of the purposes of the test (except through a web page accessible via a QR code at the end of the tests).

Regarding the test, the questions about color preferences that could help to promote concentration did not provide clear results for identifying specific color combinations, covering almost all options in the spectrum.

Other questions related to the ability to discriminate colors and color temperatures (CCTs) during tests. A good ability to distinguish differences related to saturated colors was observed, while variations in color temperature were much more difficult to capture.

The aim was to understand whether the chromatic variation caused an emotional reaction that could be perceived as an improvement or a worsening in the various scenes. The results relating to the various scenarios are represented in Figure 4.



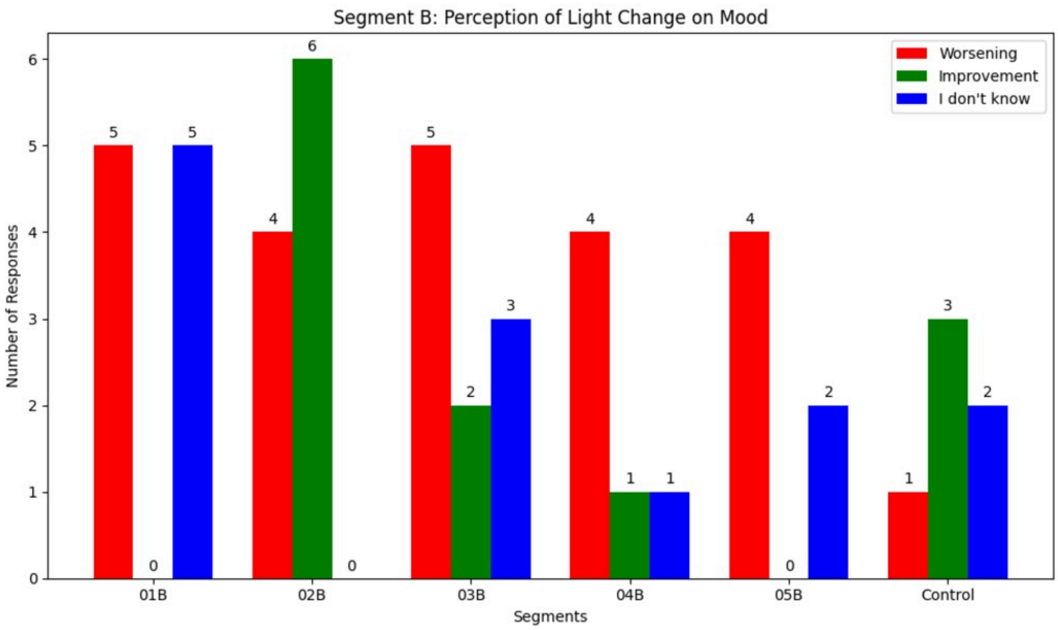


Fig. 4 - Diagram showing the results extrapolated by the questionnaires. The results refer to the color scenarios described in Figure 3.

Conclusions

The test results do not allow for a clear direction regarding emotional reactions to the colors presented. Numerous factors may have influenced this outcome. After reworking the questionnaires, it was clear that the participants were all aware of the influence of light on the well-being of individuals. Having participated in a test on light and color with such awareness plausibly constitutes an early form of bias that could have been instilled in the subjects. In fact, from the questions asked for the Q&A section of the test, it is clear that some of the subjects are aware of the mechanisms of influence of light on human physiology. This may have led to reacting to the colors presented in a way that is not entirely neutral.

The only scenes that showed a significant preference for a gradient were those ranging from a color context clearly identifiable as "cold" to one identifiable as "warm." This preference, however, may have been influenced by the season (the test took place in mid-November) and the temperature of the space where the test took place (around 19°C). Furthermore, the immobility of the subjects may have contributed to creating thermal discomfort, which in the end may have led them to prefer the transition from "cold" to "warm." The colors that could not be traced back to the "climatic" aspects of space, in fact, did not give precise results in terms of preferences. Even in the control groups, where saturated colors were excluded, exposure to a light gradient between "warm white" and "cool white" did not show appreciable preferences.

The conditions of the test themselves may have affected the psychological component of the subjects. The space was a classroom. However, there were only two people present, and the lighting used did not correspond to what the subjects (university students) were used to. This may have created an alienating effect that may have affected the emotional state. The fact that there were two subjects at a time may also have played a role; the couples who arrived independently and were not selected could have been friends, classmates, fiancés, or strangers. Being seated next to each other in an unusual setting may have influenced the emotional state. Single tests and a less characterized space (perhaps a mock-up of a residential space) would probably have had a less impactful effect on the subjects.

The choice to use the wall in front of the subjects as a secondary light source, which reflected the colored radiation, made the shade of white used for reading less identifiable. Although slight, this color pollution made it very difficult for the subjects to discriminate the CCTs used in the test.

Finally, the number of subjects was not enough to cover such a large number of scenes. To have a statistically more relevant number of samples, it would have been better to focus only on one type of scene (e.g., hot/cold scenes).

In conclusion, although we have not obtained results that allow us to work on universal guidelines on the emotional well-being of human beings through light and color, the results have shown that there is undoubtedly a correlation between these factors. The test design phase should be reviewed, and the tests should be repeated on a larger sample of subjects.

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Keynote speakers

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A gamut boundary test chart for extended colour gamut reproduction

Phil Green

Abstract

A test chart is defined for 7-colour printing. The chart is based on one already in use for four-colour process printing, but with a flexible mechanism for adding up to three further colorants used in extended colour gamut printing The chart can readily be used to determine a gamut boundary description consisting of vertex list and face list, The resulting gamut boundary description can in turn be used in the applications of gamut mapping, gamut analysis and gamut visualization.

Short Bio

Phil Green, Norwegian University of Science and Technology, Gjøvik, Norway

Phil Green is Professor of Colour Imaging at the Colour and Visual Computing Laboratory, NTNU, Norway. He is also Technical Secretary of the International Color Consortium, the body that standardizes the ICC profile format and promotes colour management internationally.

Dr. Green received an MSc from the University of Surrey, UK in 1995, and a PhD from the former Colour & Imaging Institute, University of Derby, UK in 2003.

His research interests are around cross-media colour reproduction, and include characterization, appearance, metrology, image quality and colour difference.

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Colour association: rational or groundless?

Vien Cheung

Abstract

Abstract: It has widely been agreed the strong association of colours with certain psychological or mental states. For example, often colours are expressed as being warm (e.g. red, orange), cool (e.g. green, blue), aggressive (e.g. red) or calm (e.g. blue). Is such strong association driven by our innate biological factors, accumulated through our learned life experiences or simply a part of the rules of the universe? This talk will discuss the origin of the fundamental colours, and their representations, of various historical philosophical theories around the world; in particular, an analysis on the comprehensive Chinese five-essence theory will be presented may shed light on the answer.

Short Bio

Vien Cheung, academic at the University of Leeds, UK

Vien Cheung, an academic at the University of Leeds in the UK, has authored more than 100 refereed publications in the areas of colour vision, colour science, colour imaging and colour design. Her achievements have been recognised both in the UK and internationally. Most recently, she was awarded a Gold Medal from the Society of Dyers and Colourists (2023) in recognition of her prolonged and outstanding contributions to international colour research, education and its publication. Her ethos on integrity and diversity takes her to explore how colour can be used as a vehicle to shift our ‘black and white’ judgements into a more variegated and expansive perception of the world. Vien is also active in charitable and educational colour organisations including the International Colour Association and the Colour Group (Great Britain) in which she is a Past President and the Chairman respectively.

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Colour is for Everyone: Teaching interdisciplinary colour foundations

Robin Kingsburgh

Abstract

Colour surrounds us. It is a visual language that affects how we feel and how we interact with the world. It helps us communicate and engage with our surroundings. Although colour is ubiquitous, and plays a critical role in the way we understand and shape the world, colour studies are becoming increasingly rare at both schools and postsecondary institutions worldwide. The bulk of colour education tends to reside in art and design classes, at all education levels. Yet colour plays an integral role in many disciplines, and can indeed be used as a bridge across disciplines, or as an entryway into new areas of study.

The talk will outline how to incorporate hands-on, interdisciplinary colour explorations in the classroom, at any level. It will discuss results from the Colour Literacy Project (CLP), as well as the author's experiences in teaching a multidisciplinary course about colour, which has been offered as a general elective science course at York University, Toronto, since 2000. The study of colour and colour phenomena provides an ideal entryway into science, which helps cultivate science literacy, and develop critical thinking skills. Educational materials developed by the CLP move beyond the sciences and arts, and stretch to the humanities. The CLP aims to revitalise 21st century colour education by connecting it directly to the needs of our global culture. We are currently developing and testing experiential, interdisciplinary colour resources for teachers of all backgrounds and levels. This material serves as a common foundation for everyone – not just art and design students. Preliminary results find that after undergoing our training, teachers and students alike are more engaged with colour in their surroundings, able to notice, identify and describe more colour variations, and able to ask deeper and more profound questions about colour and colour phenomena.

Short Bio

Robin Kingsburgh, Department of Science, Technology & Society, York University Toronto, CA

Robin Kingsburgh is a trained astronomer (Ph.D. in Astronomy, 1992, University College London), and a trained painter. Her artistic education comes from studies at the University of Toronto, as well as in the U.K. and France, and has paralleled her scientific development. She has longstanding interests in the intersections of art, science and education. She currently teaches various Natural Science courses at York University, Toronto, including Understanding Colour, a course on the science of colour, as well as The History of Astronomy and The Nature of Time. She has curated numerous shows and events in the Toronto area, featuring artwork inspired by the ideas and methodologies of science. She is President of the Colour Research Society of Canada, a Board member of the Inter Society Colour Council, a member of the joint ISCC/AIC Colour Literacy Project, an Associate editor for the Color Culture and Science Journal, and an elected member of the Ontario Society of Artists.

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