Color Culture and Science
Cultura e Scienza del Colore

CCSJ

Volume 15

Number 2

2023

ISSN

2384-9568

COLOR CULTURE AND SCIENCE Journal
CULTURA E SCIENZA DEL COLORE
CCSJ
jcolore.gruppodelcolore.it
ISSN 2384-9568
DOI: 10.23738/CCSJ.00
ANCE: E227716
Registrazione Tribunale di Milano n. 233: 24/06/2014
ANVUR Agenzia Nazionale Valutazione sistema Universitario e Ricerca
APeJ Academic Publications eJournal
BASE Bielefeld Academic Search Engine
DBH Database for statistikk om høyere utdanning
DOAJ Directory of Open Access Journals
EZB Elektronische Zeitschriftenbibliothek Regensburg
JURN Search tool for open access content
ROAD Directory of Open Access scholarly Resources
SCOPUS

Volume 15, number 2, September 2023
DOI 10.23738/CCSJ.150200

PUBLISHER
Gruppo del Colore – Associazione Italiana Colore
www.gruppodelcolore.org
Registered office: Piazza Carlo Caneva, 4 - 20154 Milan (IT)

PEER REVIEW PROCESS

All articles submitted to the Color Culture and Science Journal are peer-reviewed according to the following procedure:

First review level

The Associate Editors evaluate each article to determine if the topic and content are of interest to the Journal. Once the article passes the initial review, the Associate Editors select several reviewers from the Editorial Board based on their expertise in a particular subject area or topic.

Second review level

Two or three experts review each article with a blind peer-review process where the reviewers are kept anonymous. Reviewers are asked to evaluate the manuscript based on the following criteria:

- Originality
- Relevance to Journal's aims and scope
- Technical merit and/or validity
- Soundness of methodology
- Completeness of the reported work
- Conclusions supported by the data
- Correct acknowledgment of the work of others through reference
- Effectiveness of the manuscript (organization and writing)
- Clarity of tables, graphs, and illustrations
- Importance to color researchers
- Relevance to color practices

If the article is accepted with major revisions, the author(s) are asked to improve the article according to the reviewers' suggestions. The revised article will then be submitted for further review.

After collecting the reviewers' reports, the Associate Editors recommend the acceptability of the article to the Editor-in-Chief.

TOPICS

The CCSJ accept papers on a wide range of topics on color, including and not limited to the following:

1. Color and Measurement/Instrumentation. Colorimetry, photometry and color atlas: method, theory and instrumentation; quality control and food coloring, dyes, organic and sustainable color.
2. Color and Digital. Reproduction, management, digital color correction, image processing, graphics, photography, film and video production, printmaking and 3D print, artificial vision, virtual reality, multispectral imaging, data visualization. Light field imaging. Multi-sensor fusion. Color localization, recognition, HDR imaging, ADAS systems.
3. Color and Lighting. Metamerism, color rendering, adaptation, color constancy, appearance, illusions, color memory and perception, color in extra-atmospheric environments, lighting design, lighting technologies, visual comfort.
4. Color and Physiology. Mechanisms of vision in their experimental and theoretical aspects, color vision and color appearance, deficiencies, abnormalities, clinical and biological aspects, synesthesia, health, well-being.
5. Color and Psychology. Phenomenology of colors, color harmonies, color & form, perceptive, emotional, aesthetic, and diagnostic aspects.
6. Color and Production. Food and beverages, agriculture, textiles, plastic materials, ceramics, paints, gemology, color in the food industry.
7. Color and Restoration. Archaeometry, painting materials, diagnostics, and conservation techniques, restoration, and enhancement of cultural heritage.
8. Color and Environment. Representation and drawing, urban planning, the project of color, architecture, interior design, landscapes & horticulture, color and architectural syntax, territorial identities, biodiversity.
9. Color and Design. Furniture, CMF design, fashion, textiles, textures, cosmetics, food design, museography.
10. Color and Culture. Arts and crafts, history, philosophy, aesthetics, ethno-anthropology, graffiti, geology, sociology, lexicology, semantics, anthropology of vision, food culture and heritage, color naming.
11. Color and Education. Pedagogy, didactics of color, aesthetic education, artistic education.
12. Color and Communication/Marketing. Graphics, communication, packaging, lettering, exposure, advertising.

Table of Contents

Editorial

Dear Readers,

While entering the Journal's 11th year, we are glad to announce that the review of our Title is complete and that Cultura e Scienza del Colore – Color Culture and Science Journal has been accepted for Scopus.

In the last two years, the Editorial Team worked hard to improve the quality of the Journal to make it suitable for an internationally recognized database like Scopus. Scopus is Elsevier's abstract and citation database, launched in 2004, and it covers over 36,000 titles from more than 11,000 publishers in top-level subject fields. All journals covered in the Scopus database are reviewed for sufficiently high quality each year according to four numerical quality measures for each Title, like h-Index, CiteScore, SJR, and SNIP.

In the last years, we improved the Journal through different activities. We translated all the Journal's abstracts into English, especially those from the first years, specified the detailed affiliations of the board members and editors, and took different steps to raise the profile of the Journal internationally. In conclusion, we improved citations by other titles currently covered by Scopus (in May 2022, CCSJ citations in Scopus were 4, and in May 2023 were 34). CCSJ's article abstracts reached 1,400 readings (October 2022) and received an average of 29 submissions per year, with an acceptance rate of 54%. The Journal today has more than 180 users, and the numbers are growing.

Now, after the Scopus onboarding process, which will take a few weeks, all the CCSJ contents from 2019 will be included in Scopus (with some possible exceptions). Nevertheless, this step is just the start of a broader process that will raise the profile of CCSJ, and we still need you all to promote our Journal, broadcast the published articles, and be proactive in involving new authors.

In 2019, we moved the journal web management to the Open Journal System (OJS). This allows a better indexing of the published articles and guarantees compatibility with the Open Archives Initiative Protocol for Metadata Harvesting (OAI-PMH). Since our start, we have published 15 volumes for 20 issues, adopting the new numbering that publishes one volume per year with two or more issues yearly in 2019. Since 2015, we have applied blind peer review; since 2016, we have introduced the Digital Object Identifier (DOI) system. In 2020, we reviewed our archiving policy to guarantee long-term access to our issues, making agreements with the Biblioteca Nazionale Centrale di Firenze (BNCF), Italy's main official public library.

Having reached the goal of being in Scopus, we remember that our Journal is also included in other databases: ANVUR, APeJ, BASE, DBH, DOAJ, EZB, and JURN. We also recall the importance of the concept of diamond open access under which our Journal is published: all the published papers are open access, and the Journal is free for readers and authors. This goal is possible thanks to the voluntary work of some members of the Associazione Italiana Colore in the editorial committee. We thank our associate editors and the President of Associazione Italiana Colore, Marcello Picollo. A special thanks goes to Chiara

Storti of the BNCF, to Filippo Cherubini of IFAC-CNR, who manages the OJS, and to Andrea Siniscalco, the vice-president of our publishers, for the graphic support. Furthermore, a big thanks goes to the developers of the OJS, the Public Knowledge Project (PKP), which is a partnership between the University of British Columbia, the Simon Fraser University, the University of Pittsburgh, the Ontario Council of University Libraries, the California Digital Library and the Stanford University.

Enjoy the reading.

September 2023

The Deputy-Editor
Alice Plutino
University of Amsterdam

The Editor-in-Chief
Maurizio Rossi
Politecnico di Milano

Fly in color. A chromatic “model” for the cabin of a commercial aircraft

Stefano Gabbatore[1], Claudio Germak[1]

[1] Politecnico di Torino – Dipartimento di Architettura e Design, Viale Mattioli 39 – 10125 Torino, Italy; stefano.gabbatore@polito.it, claudio.germak@polito.it

Corresponding author: Stefano Gabbatore (stefano.gabbatore@polito.it)

ABSTRACT

The European research CASTLE (Cabin System Design Towards Passenger Wellbeing) puts the passenger's perception of well-being at the center of a prototype commercial aeronautics project. From this point of view, the evaluation of ergonomics and the travel experience become the objectives of an analysis of the space/context in which color, integrated with the functional components, of the shape and materials, becomes a tool for the concept design of the cabin space. The methodological approach developed therefore entrusts color to a primary role in defining the state of well-being and identity of the cabin space, through a "color model" that can be scaled in relation to the colors that each company will choose for its own color image.

KEYWORDS CMF design (colors, materials, finishes), UXD user experience design, HCD human centered design

RECEIVED 10/02/2023; **REVISED** 10/05/2023; **ACCEPTED** 15/05/2023

1. Introduction

There are two factors that have the greatest impact on the flight experience. The first is the characteristics of each passenger (habits and behaviors), while the second is represented by the relationships that the passenger establishes with the components of the cabin in the different phases of the flight. Therefore, the approach of a conscious designer will be to consider holistically the different components to improve the overall flight experience that is evaluated through the comfort indices. Referring to the evaluations of two well-known scholars of passenger comfort, Vink and Hallbeck (2012), it is agreed that the difference between comfort and discomfort depends on the interaction between the "person" (which has its own characteristics), the "furniture component" (from the seat to the carpet) and the "task" expected by the person in that specific flight phase.

Comfort is affected by a set of elements that each person evaluates with a different weight according to their perception and which can be divided into four macro-groups (Di Salvo and Germak, 2019) to be addressed in a holistic way, i.e., without a specific hierarchy:

- "accessibility to services", i.e. the offer of conditions designed for passengers to find or choose their seat, to receive information and orient themselves, to have contact with the outside world (extended view);
- "physical ergonomics", determined by the postures and movements necessary to perform an action, from sitting to accessibility to adjustments, for example, related to "proxemics", understood as the control of personal and social space (Ahmadpour, 2013);
- the "psychological microclimate", i.e., the set of environmental components such as noise and vibrations, heat, humidity and the smell of the air, and functional light (Ong, 2013);
- the “visual identity" of the space, determined by its size, organization and lighting, and of the surfaces of each piece of furniture, the perception of which is strongly correlated to the effects produced by ambient light and colors.

In recent years, all these elements have been the basis of design research for the aeronautical industry, even if individually evaluated according to different hierarchies (Torkashvand, Stephane and Vink, 2019). For example, the different relevance that the authors Bubb and Vink attribute to anthropometry in terms of ergonomics of posture and movement is known. In Bubb's assessment, anthropometry appears as the last of the factors that contribute to the perception of well-being, after smell, lights, vibration, noise and climate; evaluation overturned by Vink's analysis. These evaluations do not appear on a smaller scale aspect concerning the configuration of the cabin space and the relationships between these and the flight context. Aspects that, on the other hand, the most recent literature highlights as fundamental components of the design for the habitability of the cabin and which are influenced by the habits, behaviors and cultures to which passengers belong (Yao, Song and Vink, 2021). The integrated design of these "visual" aspects therefore concerns the setting up of the cabin as a complex space with which passengers interact during the flight phases. Today, the design makes use of overall perceptual evaluations on the four macro-groups described above, among which the visual identity is strongly influenced by light and color.

2. Fly in color. The importance of a color design

There are two approaches to the project which see, on the one hand, through the use of lights and colours, the creation of real experiential environments, capable of involving the passenger and mitigating the traditional visual discomforts associated with air travel, such as the claustrophobic sensation generated by the reduced dimensions of the space and by the perceptive insecurity determined by the tunnel effect linked to the prevailing longitudinal dimension of the passenger compartment. And on the other, trying to push this research towards the creation of virtual relationships with the outside, as in the simulations of artificial skies projected onto the ceiling and in the multimedia effects involving side walls and partition walls (Bagassi et al., 2015).

Fly in color (Bianco, 2018) thus becomes a metaphor for the importance of color choices guided by a design project that integrates the different perceptual dimensions attributed to color: psychological, visual, functional and cultural.

Based on these considerations, the UXD PoliTo Team, in collaboration with the design firm Pininfarina, has devised a cabin set-up concept aimed at reducing the tunnel effect and the claustrophobic one, integrating different design tools with each other: the configuration of the space in "virtual rooms" delimited by lighting elements and by the chromatic tonal variation of the seats in groups of three rows, the chromatic interaction of the back wall with the carpet and the sinuosity of the lining surfaces that envelop the space without continuity.

The areas of investigation on the influence of color are: the psyche, which investigates the factors of harmony/contrast, lightness/heaviness, heat/cold, liveliness or tediousness;

the visual, which detects the incidence of contrasting factors between light and dark, the saturation of the surfaces and the feeling of proximity or distance; the function, perceived as an index of hygiene or a signaling/informative element; finally, culture, an area that often associates the color choices of the cabin components (mainly the seats) with the colors of the flag, logo and airline's territory (Fig. 1).

Based on our recent semi-immersive simulations of color cabin arrangements, it appears that there is no perceptual hierarchy between these four areas. The perception of color is in fact highly subjective and linked to the passenger's previous experience, to his cultural context and to the attention he pays to the search for the motivation and meaning of a specific color. Even in the field of university teaching, we see every day how the chromatic project is one of the foundations of basic design, which cannot be separated from the theory of configuration, which must deal in an integrated way with the components of form, material and color. (Anceschi, 2006)

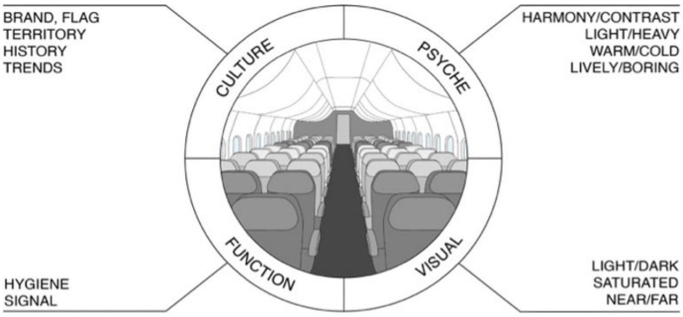


Fig. 1. The four perceptual components of color in commercial aircraft cabin.

In the cabin chromatic project these attentions are still little considered, so much so that most airlines choose the color of their set-up not on the basis of a perceptive project, but for other reasons. From our analysis carried out in 2019 (still valid in 2023) on the top 30 companies in the world according to SkyTrax (British research company)[1], it is noted that the companies show a chromatic choice based on:

a) *color brand/flag* (47%), relating to the color scheme of your brand or flag. It is a chromatic choice that is not always intuitive but in the case of saturated and contrasting colors it can translate into a lively, dynamic and not boring space. Obviously, the opposite is also true, with the risk of strong impact color associations and tiring over time, as in the case of RyanAir with its highly memorable yellow and blue hues (Fig. 2);

Fig. 2. Interior of Boieng 737-800 in Ryanair color.

b) *color culture* (27%), oriented towards the use of colors and textures referring to the company's traditions and territory. It is an appreciated chromatic choice that enriches the perception of the setting with cultural meanings. An example in this sense is that of the Etihad company (Fig. 3) which uses colors that reflect the warm colors of the territory (sand) and the sea (blue);

Fig. 3. Interior of Airbus A320 in Etihad Airways color.

c) *color context* (26%), aimed at communicating the perception of an interior space as a place of innovative technologies (see Apple Store) or prestige through harmonious colors and light colors. It is a chromatic choice with a historicized character and which requires control over the monotony and the balance between colors that follow the principle of gravity for which the heavy masses are at the bottom and with dark and saturated colors, the light ones at the top and with lighter colors and less saturated. Among the well-known examples is the AirBus Jets 350XWB designed by Pininfarina, in which the dominant white is contrasted by blue points on the seats and on the carpet (Fig. 4);

Fig. 4. Interior of Airbus Jets 350XWB in Pininfarina color.

Other data collected concern, again within the 30 companies of the SkyTrax report, the prevalent use of colors in the components that have the greatest impact on the color perception by the passenger: seats and headrests, corridor and cabin surfaces, the latter normally in homogeneous color between side and bottom walls. Obviously, the detection takes place regardless of the use of brand/flag colors, culture or context and in any case shows a prevalent adoption of shades of blue and gray with dominant red/brown. In fact, from the interviews conducted with the companies, a trend towards very cautious color projects emerges that refer to the known psychological effects activated by some colors considered relaxing and that seek harmony through the scaling of the tonality (Fig. 5).

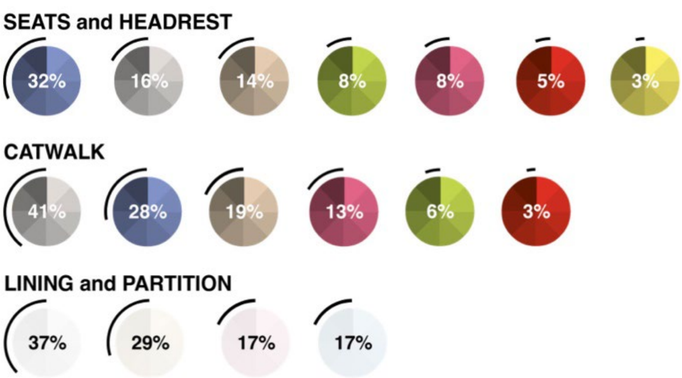


Fig. 5. Prevalence of colors in the outfitting components of the 30 aircraft selected by the SkyTrax 2019 report.

3. The chromatic setting of the space/context

Among the uncomfortable situations most perceived by the passenger, the sensation of suffocation due to the narrowness of space and the insecurity related to the lack of perception of the end of the fuselage, the so-called "tunnel effect", are highlighted. We are helped by some considerations consolidated by Gestalt research, normally applied for the perceptual evaluation of the traditional built space. It must be said that some of these principles must be further re-elaborated in consideration of the atypical space of the fuselage, which is long, narrow and with a macroscopic impact of the backrest part of the seats. In addition, the perception of chromatic comfort can sometimes be influenced, at a functional level, by the difficulty of movement both in accessing the seat and in proceeding along the corridor. Some studies (Jaglraz, 2011) suggest using Gestalt principles to evaluate the perceptual variability when not the colors vary but the contrast between them, thus obtaining effects of enlargement, narrowing, lengthening, approach (Fig. 6).

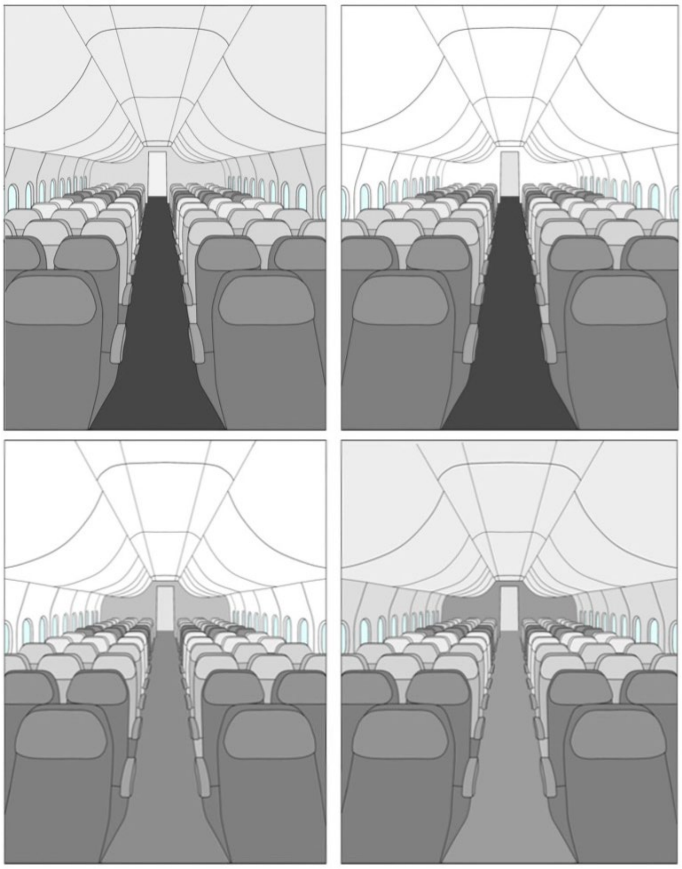


Fig. 6. Gestalt perception of possible color combinations for the cabin space.

In association with these principles, going down to the scale of the seat, it was also understood how some color combinations of this component, extracted from the models compared in the SkyTrax study, affect both the dimensional perception and the static/dynamism of the space (Fig. 7):

a. the use of scalar shades on the horizontal rows of the seats, starting from the darkest in contact with the windows, gives a perception of "widening" of the cabin through the balance of the colors, which also varies according to the day/night time slot on the way of the light coming or not from the windows;

b. the chromatic organization of the seats for columns, in alternating dark/light colors leads to an effect opposite to that described above, highlighting the length of the cabin and thus also increasing the "tunnel effect";

c. the "random" arrangement of shades in nuance gives a perception of homogeneity between rows and columns but at the same time a lively and dynamic aspect due to the contrast between the colors;

d. also, the organization by groups of rows with repetition of scalar shades considerably reduces the tunnel effect, giving at the same time a dynamic but balanced aspect in which attention must be paid to the chromatic choice for the back wall, as seen in figure 6.

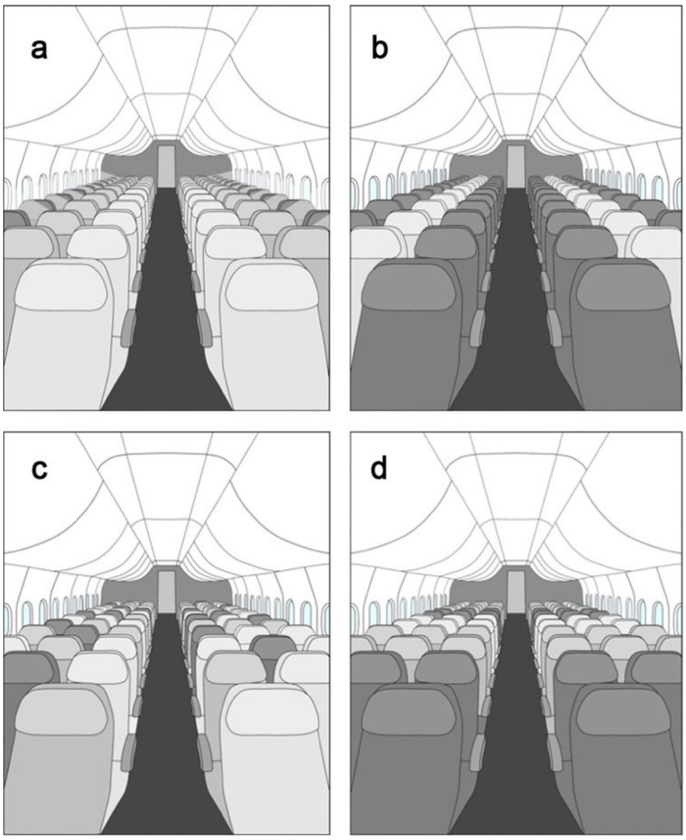


Fig. 7. Gestalt perception of possible color combinations of the seats.

4. The CASTLE chromatic model

Considering as objectives the improvement of the perceptive comfort of the cabin through the color and the possibility that this can be declined in accordance with the specific identity of each individual company, the CASTLE model is not based on the priority identification of some colors over others but on the concept of color combination. To reduce the tunnel effect and the search for a dynamic identity of the space, the model proposes the creation of "rooms" defined by a scalar and rhythmic variation of the shades of the seats, accompanied by a luminous perimeter of groups of windows and PSU (passenger service unit). The design of the different components (side and back walls, ceiling, seats and carpet) immediately integrates color as a fundamental tool for recognizing the "rooms".

In a first co-design activity with "personas" (20 males and 20 females), chosen as a sample of ideal types of passengers by age, profession and nationality, the perceptual impact of the "room model" declined in different colors. The test was conceived as a meta-project evaluation of the subdivision into "rooms", set up with different colors and scaled shades, based on the colors most used in the solutions described in the SkyTrax comparative report. The test was carried out with the projection of the cabin in real size on a large screen (7x4 m) and the personas standing, simulating his entry into the cabin from the service area. During the session, the passenger was asked to evaluate how the space and environment were perceived in terms of stress, comfort, harmony, elegance and safety, giving these factors a value from zero to five. Furthermore, in the second part of the session, to evaluate the dynamism of the chromatic combinations, different sequences of scalar shades were proposed, for a maximum of 12 hypotheses visible for ten seconds each (Fig. 8).

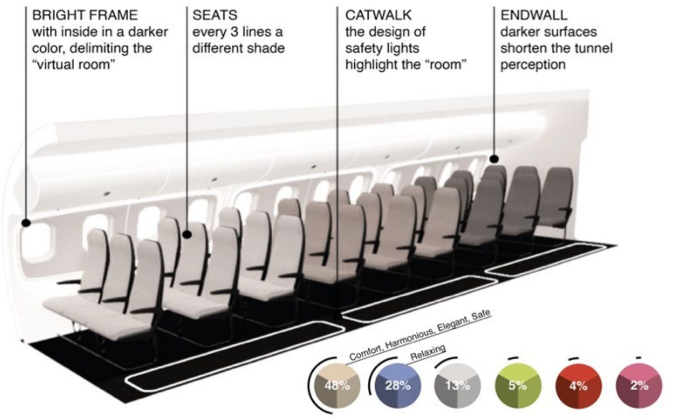


Fig. 8. Summary diagram of the elements characterizing the color in the cabin and the percentages of appreciation of the different shades.

5. The influence of light

The contemporary approach to the design of passenger cabins considers the physical chromatic research integrated with that of light. The research therefore integrates, in a holistic way, the different parameters referring to the design of the luminaires, the color rendering of the light sources and the evaluation of consumption for the purposes of energy sustainability, a very important fact in flight. The light in the cabin must ensure two conditions of a functional and expressive nature: to make actions and movements operable safely and to characterize the perception of an environment consistent with the different phases of flight with adequate intensity and colors. In addition, the lighting design must also immediately deal with the design concept of the cabin space. This is to ensure both an average homogeneous illuminance coefficient, without glare and shadows, and a perception of light comfort in the two conditions, opposite or intermediate, of active lights or off lights. Being a short/medium range aircraft, in which there are no specific flight phases such as meal or sleep, the lighting concept includes LEDs with neutral color temperatures (4000K) and intensity control managed by an onboard computer. Based on the "CASTLE chromatic model", the measurements and lighting engineering evaluations therefore concerned the control of the average illuminance values on the surfaces colored in shades of dove gray, the preferred shade for the chromatic evaluation test. The sectioning of the system allows you to activate separately, also by intervening on the intensity, the 3 types of luminaires for ambient lighting: linear ceiling; wall frames every 4 windows to delimit the "virtual room"; frames of the PSU (passenger service unit) (Fig. 9).

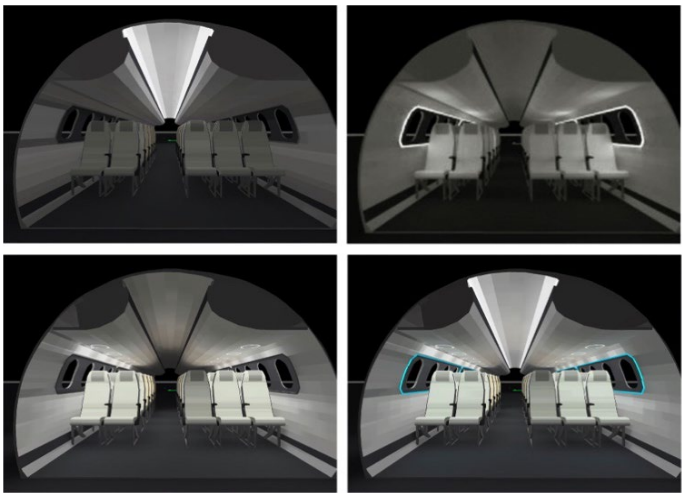


Fig. 9. The 3 types of ambient lighting fixtures active individually and (bottom right) the 3 types active simultaneously (Anna Pellegrino, Argun Paragamyan of DENERG Department – Politecnico di Torino).

6. Results and conclusions

In the near future, the concept design will be validated through final tests with users and potential customers of the aircraft, based on the perception of the various parameters that contribute to flight comfort: structural/vibrational, functional related to accessibility and movement, airiness and lighting cabin, validity of the concept design in the definition in "virtual rooms" and related "chromatic model".

Precisely the "chromatic model" opens to further research developments. On the one hand, an in-depth study of the relationships between color and texture of the seats will be initiated (introducing the parameters of roughness and three-dimensionality of the fabrics), through Eye-Tracking tests that can be carried out with the user samples already selected. On the other hand, the prototype will allow an exploration of the opportunities offered by RGB LEDs. The environmental contribution provided by these sources today is still under study but presents excellent research opportunities to improve cabin comfort in relation to both the activities to be performed in the different phases of flight, and the color rendering of the surfaces, in particular walls and seats. The well-known layout of the Boeing 737 Sky Interior, in this sense, works a bit like a gym for the chromatic combinatorial possibilities offered by the colored light sources.

In a collaboration between the Department of Architecture and Design (DAD) and the Energy Department (DENERG) of Politecnico di Torino, specific research has been launched on the use of colored light (RGB LED) in flight with an original approach. The chromatic variation of the light is in this case related, in the access, take-off and landing phases, to the temperature and humidity conditions of the external environment, to reduce the perception of sudden changes in temperature (Fig. 10).

Fig. 10. The preparation of the CASTLE cabin (concept design in collaboration with Pininfarina) with white light LEDs and possible variation of intensity and color through RGB LEDs.

7. Conflict of interest declaration

The authors of this paper declare that they do not have any actual or potential conflicts of interest, including financial, personal, or other relationships, with any other person or organization within three years of starting the submitted work. This paper is part of the work within the European research Horizon 2020 called CASTLE (CAbin Systems design Toward passenger wellLbEing) of which prof. Germak is coordinator for the Design section.

8. Funding source declaration

This research has been financially supported in the context of the European research Horizon 2020 called CASTLE (CAbin Systems design Toward passenger wellLbEing). Financial support enabled full dedication to the study.

9. Short biography of the author(s)

Stefano Gabbatore - PhD student in Management, Production and Design at the Politecnico di Torino. Member of UXD PoliTO team, with research field in physical and cognitive well-being within means of transport, analyzed through ergonomics and user experience tools.

Claudio Germak - Full professor of Design at Department of Architecture and Design (DAD) at Politecnico di Torino, and Member of Interdepartmental Center CARS@PoliTO - Center for Automotive Research and Sustainable Mobility. He also leads the UXD PoliTO team, actives in HCD/UX/UI methodologies for services/products evaluation and design. Past president of SID - Italian Design Society (2018-2021).

Notes

[1] Skytrax is a British research company operating in the field of civil aviation. It takes care of drawing up special dedicated rankings to airlines and airports. Carry out international surveys to identify the best airports, the most efficient airlines, the most qualified onboard and ground staff, the best quality onboard entertainment and catering and other crucial elements in a voyage airplane. Through these elements, Skytrax therefore wants to help the traveler choose the company that best suits their needs.

References

Akkerman, S. and Vink, P. (2018) "Improving airplane boarding time by illumination guidance," *Advances in Intelligent Systems and Computing*, pp. 220–224. Available at: https://doi.org/10.1007/978-3-319-96071-5_23.

Ahmadpour, N., Robert, J.M. and Pownall, B. (2013) "The dynamics of passenger comfort experience: understanding the relationship between passenger and the aircraft cabin interior". *The International Conference of Canadian Aeronautics and Space Institute, CASI Aero.* Toronto.

Anceschi, G., Botta, M. and Garito, M.A. (2006) *L'Ambiente dell'apprendimento: Web design E Processi Cognitivi*. Milano: McGraw-Hill.

Bagassi, S., Lucchi, F. and Persiani, F. (2016) *Aircraft preliminary design: A windowless concept*, *IRIS*. Available at: https://cris.unibo.it/handle/11585/556081 (Accessed: February 7, 2023).

Bianco, V. (2018) *Volare a Colori: La percezione del colore in cabina come elemento influenzante il benessere Durante Il Volo.*, *Webthesis*. Available at: https://webthesis.biblio.polito.it/8290/

Bubb, H. *et al.* (2015) *Automobilergonomie*, *SpringerLink*. Springer Fachmedien Wiesbaden. Available at: https://link.springer.com/book/10.1007/978-3-8348-2297-0 (Accessed: February 7, 2023).

De Crescenzio, F. *et al.* (2019) "Human centred design and evaluation of cabin interiors for business jet aircraft in virtual reality," *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 13(2), pp. 761–772. Available at: https://doi.org/10.1007/s12008-019-00565-8.

de Jong, A.M. and Vink, P. (2005) "7 Reducing Discomfort in Installation Work", *Comfort and design: principles and good practice*, pp. 85-93. CRC Press. IES (2018) *ANSI/IES TM-30-18 Method for Evaluating Light Source Color Rendition*. IES. Available at: https://www.ies.org/product/ies-method-for-evaluating-light-source-color-rendition/ (Accessed: 5 November 2018).

Di Salvo A., Germak C. (2019) "The extended comfort. Analysing the flight journey through a design-oriented approach", *XXV International Congress of AIDAA Italian Association of Aeronautics and Astronautics*, Roma, 9-12 September 2019, p. 935

Jaglarz, A. (2011) "Perception and illusion in interior design.", *International Conference on Universal Access in Human-Computer Interaction*, pp. 358-364. Springer, Berlin, Heidelberg. Available at: https://doi.org/10.1007/978-3-642-21666-4_39

Ong, B.L. (2013) *Beyond Environmental Comfort*. London: Routledge.

SkyTrax Report rating of the all-airplane companies in the world (2023). https://skytraxratings.com/a-z-of-airline-ratings

Torkashvand, G., Stephane, L. and Vink, P. (2019) "Aircraft Interior Design and satisfaction for different activities; a new approach toward understanding passenger experience," *International Journal of Aviation, Aeronautics, and Aerospace* [Preprint]. Available at: https://doi.org/10.15394/ijaaa.2019.1290.

Vink, P. and Hallbeck, S. (2012) "Editorial: Comfort and discomfort studies demonstrate the need for a new model," *Applied Ergonomics*, 43(2), pp. 271–276. Available at: https://doi.org/10.1016/j.apergo.2011.06.001.

Winzen, J., Albers, F. and Marggraf-Micheel, C. (2013) "The influence of coloured light in the aircraft cabin on Passenger thermal comfort," Lighting Research & Technology, 46(4), pp. 465–475. Available at: https://doi.org/10.1177/1477153513484028.

Yao, X., Song, Y. and Vink, P. (2021) "Exploring factors influencing visual comfort in an aircraft cabin.", 3rd International Comfort Congress 2021, Nottingham.

Zhang, L., Helander, M.G. and Drury, C.G. (1996) "Identifying factors of comfort and discomfort in sitting". Human factors, 38(3), pp.377-389. https://doi.org/10.1518%2F001872096778701962

The boundaries between light and color in architecture: the different lighting solution

Paola Bertoletti

Department of Design, Politecnico di Milano

Corresponding author: Paola Bertoletti (paola.bertoletti@polimi.it)

ABSTRACT

Light and color are innate characteristics in architecture. Hardly an environment, a building, or a monument can be devoided of light and color. The reason is simple. Even if humans holistically perceive what surrounds them, sight is generally the first sense activated in the discrimination of the environment.

Lighting technology and colorimetry are inextricably connected. The visible spectrum and our sensibility to different radiations, allow us to perceive colors and experience space. This assumption also implies that its indeed possible to achieve significant changes in a space, with the sole use of light and color.

The relationship between light and color is well known from a photometric and colorimetric point of view; however, the relationship between these two actors has different meanings in the symbolic and interpretative sphere. This article aims to explore these aspects. The color is not an intrinsic physical property of the objects; the lighting designer must be aware that changing the technology or the propriety of light sources directly affects the chromatic aspect of an object and as such perceptions of architecture and symbolism of its color.

This article wants to demonstrate that seeing architecture, means interpreting a context through its colors and shapes.

KEYWORDS Light, Color, Visual perception, Lighting strategies, Architectural lighting

RECEIVED 03/05/2023; **REVISED** 10/06/2023; **ACCEPTED** 12/06/2023

1. Introduction

Light invites us to enter a space, highlights details, and fascinates us. Light plays a crucial role in our ability to see and appreciate past and present architecture. Light is one of the most critical factors in architecture and color is one of its properties. Together, they shape our perception of the built environment and play a critical role in interacting with architectural spaces.

Lighting and its colors have not only functional features but also add emotional value to architecture by helping to create an experience for those who inhabit the space. Architecture achieves its goal through natural and artificial lighting by showing off its shapes, textures, and details.

Color is another important element in architecture that influences our emotional and psychological response to space (Radwan and Helwan University, 2015). Architects use color strategically to evoke certain moods, create visual harmony or contrast, and express the intended character of a building. From the exterior façade to the interior finishes, the choice of color can influence the perception of a building and highlight or downplay certain architectural features.

Light and color work in harmony to determine the character, mood, and visual impact of architecture. They allow us to appreciate the interplay of form, space, and materials and contribute to understanding architectural concepts, intentions, and narratives. Without light and color, our architectural experience would be severely limited, as they provide the necessary visual cues and stimuli that enrich our perception and create meaningful connections between us and the built environment.

2. Lighting strategies: aspects and approaches

To achieve a harmonious balance between lighting and architecture, it is essential to consider the three basic elements of architectural lighting: Aesthetics, Functionality, and Efficiency (Lam, 1977).

In aesthetics, designers examine the emotional impact of light in architecture. Aesthetic considerations refer to how lighting enhances the visual appeal and ambiance of a space. This can be achieved by highlighting architectural features, emphasizing textures and materials, providing focal points, and creating a desired atmosphere. The goal is to create a visually appealing environment that complements the architectural design and evokes the desired emotional response.

The second fundamental aspect is the function of light. Regardless of the aesthetic aspect of the designed light, the light always has a very specific purpose, which is to allow the process of vision. Functionality refers to the practical aspects of lighting in architecture, meeting the specific requirements of the space and its users.

Today, the aspect of efficiency is fundamental. Creating a fantastic lighting project is an accomplishment in itself, but it is even more impressive when the project is also extremely energy efficient. Efficiency focuses on optimizing energy consumption and minimizing environmental impact without compromising the aesthetic and functional aspects of lighting.

Balancing aesthetics, function, and efficiency in architectural lighting requires a thoughtful and holistic approach. This includes collaboration between architects, interior designers, and lighting designers to ensure that lighting design enhances architectural intent, provides necessary functionality, and promotes energy-efficient practices.

Lighting design is a relatively young profession introduced by Richard Kelly in the second half of 1950, using the title "architectural lighting consultant" (Petty, 2014). Before the Second World War, it was common to use light according to the theory of the quantitative approach: since electric light was finally available, it was common to produce large amounts of light without thinking about the people or any aesthetic effect. It is only after the Second World War that people begin to think not only about lighting but about how to illuminate, that is, studying the right amount of light that allows a proper vision of the surroundings. This theory is called a qualitative approach (Ganslandt and Hofmann, 1992).

The figure of the contemporary lighting designer, more complex than the profession described by Richard Kelly, is defined by the energy crisis of the 1970s with the oil embargo and the resulting high energy costs. If before the energy crisis, the general rule of lighting designers was "more light, better vision," after the energy crisis the mantra changed to "the right amount of light in the right place at the right time." (Neumann *et al*, 2010). Most light must now reach its destination with as little waste as possible to achieve the highest efficiency (Skarżyński and Żagan, 2022). Aesthetics, function, and efficiency are thus the three characteristics that the lighting designer must consider when looking at a project as a unity of light and color.

3. Light in Architecture

In architecture, there is usually a concern about the balance between light and shadow, but this is always linked to the crucial and interconnected relationship between light and color. Light is the source that reveals and interacts with colors, allowing the perception and experience of the full range of hues in a space.

In the context of historic architecture, light helps reveal the intricate details, textures, and shapes of buildings. Many architectural structures from the past were designed with a deep understanding of daylight and its interaction with space, strategically using natural light through the openings to create dramatic effects and highlight certain structural elements. The play of light and shadow in Gothic cathedrals, for example, highlights the beauty of their intricate stained glass windows and sculptural details (Górczewska, 2011).

Light is also a fundamental design aspect in contemporary architecture. Today, various techniques are used to manipulate and control natural and artificial light to create specific atmospheres, evoke emotions, and highlight architectural features.

Overall, it is crucial to understand the interplay of natural light, artificial lighting, and color as essential components in shaping the character and experience of architectural designs, where these elements work synergistically to support the functionality, aesthetics, and desired user experience of the space.

Architecture and light have always been interdependent concepts. Le Corbusier believed in the transformative power of light in architecture and considered light an essential element that shapes space and materials. Le Corbusier states, "Architecture is the learned game, correct and magnificent, of forms assembled in the light " adding "Our eyes are made to see forms in light" (Le Corbusier, 2013; Plummer and Corbusier, 2013). This relationship between light and architecture inevitably takes place in space.

Le Corbusier's use of natural light inspired Bruno Zevi's approach to light, but he differed from others in that he viewed light as a fundamental material for architectural design. Zevi believed that light could be used to create spaces that were emotionally charged and that it could be used to shape the form and character of a building. If other architects focused on functional lighting, Zevi believed that lighting could shape the unique identity of a place by focusing on the emotional and esthetic aspects of light in architecture. When asked what constituted the atmosphere in architecture, Zevi replied, "There's no doubt about it, the light in the space." (Cirillo, 2001)

It was Sigfried Giedion emphasized how closely light is linked to the definition and perception of space, writing, "Light gives the feeling of space. Darkness dissolves space. Light and space are inseparable. When light is turned off, the emotional content of space disappears and becomes impossible to grasp. When it is dark, there is no difference between the emotional evaluation of space and that of a well-designed interior" (Giedion, 1982). Giedion's words perfectly explain the task of the lighting designer, a very important figure for some architects of our time.

Zaha Hadid, often described as the grand dame of contemporary architecture, considered artificial and natural lighting an integral part of her architectural vision. She often collaborated with lighting designers to develop customized lighting solutions that complemented the complex geometries and fluid forms of her buildings (Sebastian *et al.*, 2018). For Hadid, lighting was an essential tool to show and interpret the forms and textures of her architecture.

4. The perception of light and color

Color is imperceptible without light. The viewer is strongly stimulated by color, a phenomenon that results from the interplay between the molecular composition of an object, specific wavelengths of light, and the neurological structure of an organism. Without any of these elements, there would be no color perception. Color, then, is not an inherent property of an object, but rather an event that results from the intertwining of these factors (Bryant, 2011). The proprieties of the material that composes the object, the position, and the physical condition of the viewer are all crucial factors, as is the role that light plays in all perceptions. In addition, color is fundamental in representing architectural elements, their concealment, and their impact.

In general, architecture can be considered a set of inseparable qualities: space, movement, textures, objects, details, and surfaces flooded with light and colors. In both an interior and exterior environment, we experience color and light as the result of perceptual and emotional adaptation.

Arne Valberg states a fundamental difference between physical stimulus quantities, photometric, colorimetric, or otherwise, and the subjective qualities that are perceived (Valberg, 2005). Spatial perceptual situations are very complex. As we move through space, our perception and experience of the spatial totality are affected sequentially and simultaneously by adaptation to different lighting and then also by the interaction of the light with color. Perception and experience thus result from our interaction with the environment, which cannot be calculated only photometrically, as is often done.

Color and light in architecture have not only a functional sense, but also an emotional sense, as they influence our experiences, feelings, and our physiological well-being, and are thus relational qualities that arise from human participation and action in space. If the designer aims to consider light and color more connectedly, the field is vaster than simple good lighting practice.

While it is true that light and color are commonly perceived through the human visual system, it is equally true that the perceived sensations are full of meaning (Little, 2014). Because they are sensory experiences, the perception of light and color can be understood differently, from the rational view to the purely subjective view of 'liking or disliking' to culturally influenced meanings.

With this variety of actions, there are different experience levels with light and color. They range from experiences based on perception (formal aspects of color and light), to direct experiences with the surrounding world (expressions of color and light), to indirect experiences (conventional meanings of color and light) rooted in culture and history, such as traditions, customs, trends, art, and so on (Klarén *et al*., 2013).

Rudolf Arnheim analyzes the creation process of artistic perception and talks about form, space, movement, and even color and light, as fundamental aspects for visual understanding. He writes, "If we had wanted to begin with the first causes of visual perception, a discussion of light should have preceded all others, for without light the eyes cannot perceive form, color, space, or movement" adding "But light is more than just the physical cause of what we see. It also remains psychologically one of the most fundamental and powerful human experiences" (Arnheim, 1997).

5. Light and color in the lighting project

Color is not a physical property inherent in what we see; thus the proprieties of light play a fundamental role in lighting design. Color and light are described within specific Spectral Power Distributions, therefore, without light, color cannot exist, but often this fundamental matter is not considered. Not considering that light and color in architecture are two different but inseparable aspects of the same issue, generally, different paths are followed. In lighting research, it mostly aimed to solve aspects of visibility and comfort, while in the field of color, attempts have been made to solve the needs of design, style, and fashion. Today, however, in particular through psychophysics, which is the subfield of psychology that studies the relationships between physical stimuli and sensory systems, it has been possible to define some fundamental aspects of color and light, underlining their ability to contribute to human well-being.

In the process of lighting design, it is necessary to clearly understand how the space is experienced by users, both for the creative process and for the critical distance. Very often designers tend to improve an object's appearance or interpret a place's mood when in reality the aim should be to promote the psycho-physiological well-being of individuals.

Designing color and light implies that insiders have a solid understanding of the conditions that govern visual perception (Klarén, 2013). Light and color condition us through the visual system, through non-visual paths, and also by affecting the circadian system. The Spectral Power Distribution of light and our non-linear sensibility to colors can significantly alter our experience of space. Concerning colored lights, it is typical for individuals to think of vivid and saturated colors (Labrecque and Milne, 2012). Rich and saturated colors are only a small portion of what today's artificial lighting technology has made available to us. Even white light could by now be defined as colored light given the range of white tones available to illuminate our environments. We are constantly flooded with color from both our natural and manmade surroundings. Colored artificial light, however, does not share the same eminence as daylight. For many, the colored lighting, fixed or dynamic, should be designed only for theatre, art installations, or special events, and not used to illuminate our architecture for the everyday. Colored lighting schemes in architecture have received mixed reactions from the public as it is difficult to relate to or understand the message intended by the designers.

Lighting designers are well aware of how colors and materials can appear differently under these lighting conditions, but they harness this knowledge to modify and enhance the perception of space, as well as to visually communicate with people. With dynamic colored lighting, a space can seem larger or smaller, darker or brighter than it really is, not only using the balance of light and darkness as a focus of the design but also through color. For instance, when a room is bathed in monochromatic light, the surfaces and textures seem to blend together, allowing to stand out new contrasting focal points. On a larger scale, many monuments and cities are being designed with color-changing lighting.

6. The different lighting solutions in an urban environment

The perception of a city is strongly connected to its lighting creating iconic landmarks that can improve the "wayfinder" concept (Lynch, 2008). Lighting with its color and shapes enhances the visibility and usability of urban spaces transmitting messages and communicating with people as a perfect marketing tool (Schielke, 2015).

Fig. 1. White light for the façade of Lit Brothers, Philadelphia, USA. Ph. © Jeffrey Totaro, Color Kinetics

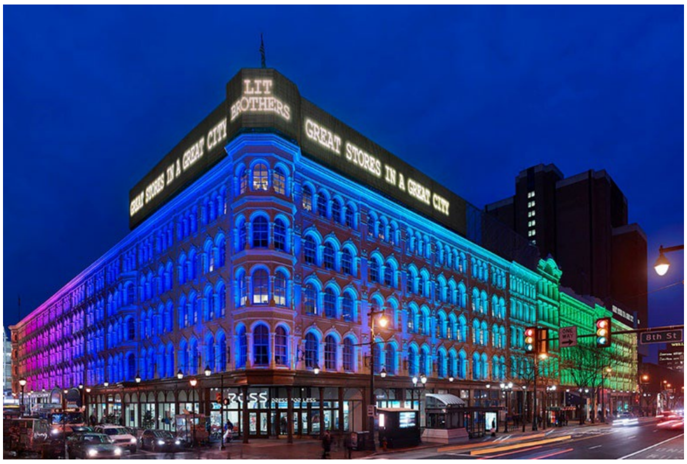


Fig. 2. Lit Brothers facade is illuminated with dynamic colored lighting to reflect holidays, local celebrations or world events. Ph. © Jeffrey Totaro, Color Kinetics

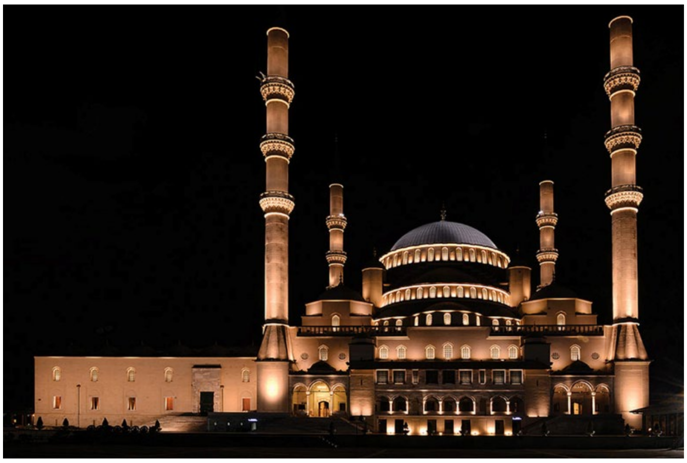


Fig. 3. The lighting of Kocatepe Mosque in Ankara, Turkey, uses tunable white technology to highlight all of the building's architectural details. different color temperatures of white light. Ph. © Istavrit Agency, Color Kinetics

With the addition of lights, projections, and video, the facades are able to evoke emotions in the viewer. Today, technology and creativity are working together and giving life to new and dynamic architectural lighting solutions that offer cities the opportunity to interact more and more with their public. This can be achieved with different lighting solutions depending on the project idea, from simple static light to advanced individual pixel-controlled solutions.

The fixed lighting of facades or monuments convey emotions in a static way, showing the architecture in a stable and immutable manner. This type of lighting can be done with white tones or color. This approach is sometimes, and erroneously looked as simple. Architectural lighting designer must first know the aim of the project. This includes determining whether the lighting should be studied to create an image of the fictitious facade or to show the architecture as it is typically seen in daylight, accentuating specific characteristics.

This type of lighting project will involve deep study of the history and architectural style of the building itself (Di Salvo, 2015).

Static lighting allows only the control of the light intensity, offering the possibility of adapting to changes in the environment and daylight conditions.

To achieve a change in the image of the facade in a subtle and non-invasive way, the optimal solution is to use tunable white lighting, technology that can adjust the color temperature by combining multiple white lighting sources. The color temperature of lighting has a significant impact on the architecture. The possible variations in color temperature from warm white to cold white can change the facade's appearance and thus convey various emotions or enhance different textures and colors.

The achievement of dramatic and more evocative effect, often implies that cities are to be illuminated with soft or saturated colors. Lighting can be programmed by changing colors only at specific times allowing the architecture to be temporarily transformed into a living object of the urban landscape. When colored light is designed in the urban landscape, however, the lighting designer must carefully consider every element that will illuminate and with which colors since it will be linked to an image and an experience that the observer will live and admire as if he was inside a painting.

Selecting a functional and easily achievable technology will be essential whichever solution is chosen.

Today technology is very advanced and with it the complexities. It is therefore crucial to choose intuitive solutions that allow the integration of lights and interactive technologies and that give the possibility to control the entire system simply and effectively. Only in this way, will technology not become an obstacle to creativity.

Fig. 4. The facade of County Hall, London, UK, is illuminated to full height with a uniform color-changing light, making the building an iconic and eye-catching landmark on the South Bank both by night and by day. Ph. © Redshift Photography, Color Kinetics

6. Conclusions

Although colored artificial light sometimes incurs a negative reception from users, it should be seen as an exciting and powerful tool that can produce impressive results when used correctly.

The union and play between light and color, when designed with care, improve the identity of an environment by creating a new character and allowing those who live it a unique experience, sometimes managing to tell a story with a fascinating theatrical effect.

The fundamental aspects are in the choice of color, in the way it is applied, and the understanding of its effects. However, it is essential to know the basic principles that include the use of colors such as the right choice of contrasting tones to create depth or to highlight, or to understand how color can alter the appearance of textures, materials, and space. Color science must become a technical basis for lighting designers to be able to implement the right illumination with the most appropriate technology.

The question "Why color?" should be the first thing that crosses the mind of lighting designers willing to use colored light.

7. Conflict of interest declaration

The author of this piece of research declares no known conflict of interest with other people and/or organizations.

8. Funding source declaration

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sector.

9. Short biography of the author

Arch. Paola Bertoletti - Lighting designer Architect. She is a teacher at the Master in Lighting Design and Technology and Master in Interior Design of the Politecnico of Milan and adjunct professor of the Master's degree course in Lighting Design and Bachelor's degree course in Design Methods at the School of Design of the Politecnico of Milan. She collaborates with Laboratorio Luce of Politecnico di Milano.

Licensing terms

References

Arnheim, R. (1997) *Art and visual perception: a psychology of the creative eye*. Expanded and revised edition 1997. Berkeley, Calif.: Univ. of California Press.

Besenecker, U.C. and Krueger, T. (2015) 'Luminous Color in Architecture: Exploring Methodologies for Design-Relevant Research', *Enquiry The ARCC Journal for Architectural Research*, 12(1). Available at: https://doi.org/10.17831/enq:arcc.v12i1.392.

Bryant, L.R. (2011) *The democracy of objects*. First edition. Ann Arbor: Open Humanities Press (New metaphysics).

Cirillo, F., editor (2001) *Saper credere in architettura : cento domande a Bruno Zevi*. Napoli: CLEAN (Interviste ; 1). Available at: http://digital.casalini.it/9788884972729.

Di Salvo, S. (2015) 'Cultural content of lighting for the discovery of archaeological heritage', in *Architecture Anthology I: Architectural Construction, Materials and Building Technologies*. Athens Institute for Education and Research (ATINER), pp. 47–58.

Dudchenko, M., Mironenko, O. and Milavski, S. (2020) 'RELATIONSHIP BETWEEN A LIGHT, COLORS AND A SPACE IN URBAN ENVIRONMENT', *Technical Aesthetics and Design Research*, 2(1), pp. 19–26. Available at: https://doi.org/10.34031/2687-0878-2020-2-1-19-26.

Dugar, A. (2018) 'The role of poetics in architectural lighting design', *Lighting Research & Technology*, 50(2), pp. 253–265. Available at: https://doi.org/10.1177/1477153516664967.

Elnaggar, H. (2022) 'Illumination and Color in Interior Design of Living Room', *Journal of Design Sciences and Applied Arts*, 3(1), pp. 50–63. Available at: https://doi.org/10.21608/jdsaa.2021.76256.1112.

Ganslandt, R. and Hofmann, H. (1992) "The principles of perception-oriented lighting design". In: *Handbook of Lighting Design*. Braunschweig/Wiesbaden: Vieweg Verlag, pp 115-116

Giedion, S. (2009) *Space, Time and Architecture: The Growth of a New Tradition, Fifth Revised and Enlarged Edition*. Harvard University Press. Available at: https://doi.org/10.2307/j.ctv1bzfnzf.

Górczewska, M. (2011a) 'Some aspects of architectural lighting of historical buildings', in. *LIGHT 2011*, Poznan, Poland, pp. 107–116. Available at: https://doi.org/10.2495/LIGHT110101.

Górczewska, M. (2011b) 'Some aspects of architectural lighting of historical buildings', in. *LIGHT 2011*, Poznan, Poland, pp. 107–116. Available at: https://doi.org/10.2495/LIGHT110101.

Kaçel, S. and Lau, B. (2018b) 'Louis I. Kahn and Richard Kelly: collaborative design in creation of the luminous environment', *Architectural Engineering and Design Management*, 14(4), pp. 306–316. Available at: https://doi.org/10.1080/17452007.2017.1399857.

Kelly, R. (1952) 'Lighting as an Integral Part of Architecture', *College Art Journal*, 12(1), p. 24. Available at: https://doi.org/10.2307/773361.

Labrecque, L.I. and Milne, G.R. (2012) 'Exciting red and competent blue: the importance of color in marketing', *Journal of the Academy of Marketing Science*, 40(5), pp. 711–727. Available at: https://doi.org/10.1007/s11747-010-0245-y.

Lam, W.M.C. (1977) *Perception and lighting as formgivers for architecture*. New York: McGraw-Hill.

Lynch, K. (2008) *The image of the city*. 33. print. Cambridge, Mass.: M.I.T. Press (Publication of the Joint Center for Urban studies).

Neumann, D. (2011) 'The Structure of light: Richard Kelly and the illumination of modern architecture', *Choice Reviews Online*, 48(12), pp. 48-6717-48–6717. Available at: https://doi.org/10.5860/CHOICE.48-6717.

Plummer, H. and Le Corbusier (2013) *Cosmos of light: the sacred architecture of Le Corbusier*. Bloomington and Indianapolis: Indiana University Press.

Poldma, T. (2009) 'Learning the Dynamic Processes of Color and Light in Interior Design', *Journal of Interior Design*, 34(2), pp. 19–33. Available at: https://doi.org/10.1111/j.1939-1668.2008.01017.x.

Radwan, A. H. and Helwan University (2015) 'Color in Architecture is it Just an Aesthetic Value or a True Human Need?', *International Journal of Engineering Research and Technical Research*, 04(12), pp. 523-533. Available at: https://doi.org/10.17577/IJERTV4IS120587.

Schielke, T. (2015) 'Influence of Lighting Design on Marketing Communication', *LEUKOS*, 11(3), pp. 109–124. Available at: https://doi.org/10.1080/15502724.2015.1020949.

Skarżyński, K. and Żagan, W. (2022) 'Quantitative Assessment of Architectural Lighting Designs', *Sustainability*, 14(7), p. 3934. Available at: https://doi.org/10.3390/su14073934.

Sokolova, M. and Silkina, M. (2018) 'Architectural lighting in search of identity: The environmental approach', *SHS Web of Conferences*. Edited by R. Narboni et al., 43, p. 01008. Available at: https://doi.org/10.1051/shsconf/20184301008.

Valberg, A. (2005) *Light vision color*. Hoboken, N.J: John Wiley & Sons.

Wang, Z. *et al.* (2020) 'Lighting Style and Color Temperature to Emotion Response in Architecture Illumination of the Historic Buildings in Dalian', in *2020 International Conference on Computer Engineering and Application (ICCEA)*. *2020 International Conference on Computer Engineering and Application (ICCEA)*, Guangzhou, China: IEEE, pp. 613–617. Available at: https://doi.org/10.1109/ICCEA50009.2020.00134.

Experience of place: colour and lighting design methods in the process of inclusive housing projects.

Lorrain Caumon[1,2,3], Georges Zissis[1], Céline Caumon[2]

[1] *LAPLACE, UMR5213 (CNRS, INPT, UT3), Université Toulouse III, France; georges.zissis@laplace.univ-tlse.fr*

[2] *LARA SEPPIA, EA 4154 (UT2J), Université Toulouse II, France ; celine.caumon@univ-tlse2.fr*

[3] *SOBRIM Company - HARANAM concept, Bayonne, France; l.caumon@sobrim.fr*

Corresponding author: Lorrain Caumon (lorrain.caumon@laplace.univ-tlse.fr)

ABSTRACT

The periods of confinement that we have experienced have highlighted the proven impact of the quality of living spaces on their occupants. While the health crisis has been at the heart of many debates in recent years, it has only served to highlight the issues at stake and to accelerate research into the quality of life in collective housing. The notion of quality of life often translates into the ambition to build responsible buildings, responding to issues of air quality, water quality, energy saving (etc.), however, the design of visual environments must be considered in the same way as the other intrinsic characteristics of the dwelling as elements contributing to meeting the expectations of inhabitants in terms of health and quality of life for all.
Our research has revealed that the architecture of collective housing often suffers from a lack of care when it comes to the design of their interior spaces. This can have detrimental effects on users. We hypothesised that a transdisciplinary approach (physicist/colour designer) based on optimising ambient factors could improve the quality of use of these spaces. The objective was to demonstrate scientifically how the spaces in which we live influence our quality of life. The results obtained offer two levels of analysis. The first, theoretical, contributes to the advancement of the issue of environmental perception. The second, practical, presents a research-creation protocol that can help designers to create more sensitive and inclusive communal spaces by optimising the factors of colour, light and materials. In conclusion, the interpretation of the results obtained from the projects validated the undeniable effectiveness of this multidisciplinary protocol.

KEYWORDS Light design, Colour design, Visual comfort, Property developer, Collective housing.

RECEIVED 24/02/2023; **REVISED** 06/05/2023; **ACCEPTED** 26/05/2023

1. Introduction

1.1 *Issues addressed*

Currently, 31.6% of the French population lives in a collective dwelling, i.e. nearly 21 million people (Henri Albertini *et al.*, 2018). At the same time, around 12 million French people are affected by a disability, including 1.5 million with a visual impairment and 850,000 with reduced mobility, due to various pathologies, life accidents or age (Mormiche, 2001). Similarly, the increase in life expectancy is indeed a warning factor that should challenge us in our approach to designing an inclusive space, because in 2050, metropolitan France will have between 58 and 70 million inhabitants, by which time more than a third of the population will be over 60 years of age, which will require numerous adjustments to our daily living environment (Brutel, 2002). Moreover, in recent years, home care has been preferred to institutional care, especially for people with a slight loss of autonomy (Kubiak, 2012), so for all these people, the positive and safe perception of the daily environment must become an important issue for designers of collective housing. Thus, it is essential to take into account the parameters of colour, light and materials in this type of environment, as factors of atmosphere and comfort of use. These elements have led us to question how professionals of collective housing take into account the characterisation of the CLM (colour-light-materials) approach in the design of inclusive common spaces, where plural human needs must be at the centre of the reflections.

1.2 *Reassessment of standards*

For many years, the authorities have placed man and his pluralitý at the heart of many laws that come to life within new architectural projects. However, these laws are very often set up and governed by recurrent and unwavering norms, averages and conformities; yet, if we stick to the strict observance of these, as man does not respond to any average it is obvious that many gaps remain. Furthermore, in the literature on environmental factors, the subjective part in the assessment of environmental factors is often mentioned, but there are very few indicators that refer to this. Mudri (Mudri, 2002) states that in studies using interviews and observations, the dimensions of the personalitý and disabilities of the subjects have generally not been studied in detail and the subjects are therefore considered 'average'. As a result, it goes without saying that strict adherence to these rules and averages does not guarantee the success of an architectural project, particularly in visual ambience design.

2. Transdisciplinary approach

2.1 *Research context: transdisciplinarity as a lever for social innovation.*

Today, we note that more and more designers in the field of architecture are becoming aware that the quality of life in collective housing requires the emergence of interdisciplinary designs and are committed to placing human concerns at the heart of the issues. Therefore, our study presents a design method combining collaborative and evolving expertise for the benefit of tomorrow's inclusive housing. Attentive to emerging demands, the company Sobrim, an expert in Basque real estate development, took the initiative in 2018 to create a multidisciplinary centre of expertise. Its ambition is to go beyond the strict field of property development, as the methodology applied to this new approach, known as Haranam (SOBRIM - HARANAM), is experimental, global, transversal and multidisciplinary. It is based on a synergy of work between experts from different fields. During dedicated days, doctors, physicists, doctoral students, building and human science experts are invited to discuss the complexity of the issues at stake in order to come up with concrete solutions and specifications that meet the expectations of tomorrow's housing.

The study proposed here questions the way in which doctoral research in CLM is taking up these new design methods. The answers and methodologies provided are anchored in a research-creation approach, addressing an interdisciplinary design protocol, conducted in the real estate development sector. To this end, we will present a case study and a design protocol in terms of colours (colour counter-types), lighting (characterisation of light) and soundings (characterisation of feelings), with the aim of accompanying designers in a process of designing interior visual environments and chains of movement that are truly adapted to the conscious and unconscious needs of their inhabitants.

2.2 *Research-creation and creation-research in colour, light and matter.*

In the literature of cognitive sciences and psychology, there is little research on the role of colour in its relationship to space and in particular in the spatial orientation of people. However, we know that a visual environment adapted (Damelincourt *et al.*, 2010) to the pathologies of people with disabilities has positive effects, but must respect a certain number of criteria such as an appropriate amount of light, contrast and spatial distribution. Various design factors can enhance or hinder the human response, and weaken environmental visual cues.

We therefore hypothesised that colour in the architectural environment of multi-family dwellings could support spatial location and orientation, particularly for people who are disoriented, less responsive to conventional signage systems (Bay and Fayolle, 2020) or have certain age-related visual impairments, (see Figure 1).

Fig. 1 . Illustration of age-related visual pathologies. Résidence Opalescence, Bayonne, SOBRIM, Ambre Building, floor n°2.

In doing so, this empirical approach will hopefully lead to a reflection on colour in collective housing environments. Inherited from hygienic and standardised norms, we note, even today, that few works integrating colour are the object of a voluntary approach. The choice of colours and materials often depends on the tastes of the project manager and the usual validation of the client, but what seems to be a secondary issue is in reality a key point in the evaluation of the success of an architectural project. The results of this study will allow the development of a creative protocol that will help the developer to design visual environments that are adapted to the needs of all inhabitants.

The main results expected from this study are:

1.To improve the analysis and interpretation protocol for defining comfortable visual environments.

2.To develop tools to simulate the lighting environment in the design phase of the programme.

3.Facilitate the integration of the results of this study by professionals.

3. Methodology of analysis and creation

3.1 *Colour-material, colour-light*

The protocol presented is based on a combination of chromatic expertise (colorimetry) concerning the choice of materials, textures and finishes, with an emphasis on colour for its plastic character; and lighting (light characterisation) concerning the quantity and colourfulness of light, with particular emphasis on different colour temperatures. This study focuses mainly on the chains of movement, i.e. the common spaces and the interior horizontal circulations. Indeed, the visual atmosphere of these spaces must create a feeling of welcome, visual comfort and safety for all users, of all ages, day and night. The method used will therefore serve to create coherence and harmony between the exterior landscape treatments and the interior colour and light treatments in order to create an intuitive and inclusive chain of movement.

The protocol and analyses presented were carried out between April 2019 and June 2022 on the site of the "Opalescence" residence in Bayonne built by the property developer SOBRIM (Basque Country, France).

The method was divided into three stages: capture, creation and feedback:

3.2 *Step 1: Recordings*

The first phase consisted of collecting photographs of the construction site over a period of 8 consecutive hours, the inventory of the existing situation being an essential phase before any project. Equipped with cameras, this preliminary analysis was accompanied by a walk around the site.

Photographs cannot faithfully reproduce the colours of a palette. However, they are essential graphic documents for memorising, visualising and disseminating information (Lenclos and Lenclos, 2016). Most colour studies use photographic investigations to support colour surveys. In our case, photography was used in two approaches, one aimed at establishing an inventory of the surrounding

urban colours and forms, the other a colour and light diagnosis to judge the appearance of the site under cyclical light conditions. This step was a means of transcribing and analysing the experience of a space.
The second step was to reference the colours of the site using countertypes. In our study, the colour survey consisted of observing the colours of the environment and the architectural elements surrounding the project and comparing them to reference colour samples. Here we used the colours of the NCS colour chart. The Natural Color System is a universal system used for standardised colour communication, based on an intuitive coding system designed for human vision. This reference system allows us to communicate colours universally in different fields of application. This representation has also allowed us to translate these colour readings into values using the CIE XYZ L.a.b system, taking into account the logarithmic response of the eye, but also the specific characteristics of coloured surfaces with their luminance index.

3.3 *Step 2: Creation*

The first phase consisted of a study of the existing light, the environment, the chromatic and architectural identity of the site. Each environment has a unique identity, of which colour and light are part. The mission of the CLM research engineer must necessarily include a diagnosis of the existing environment. This stage defines the way in which we will approach the existing environment and certain elements in relation to the project, but also in relation to the wishes of the developer in terms of the expected aesthetic and functional ambitions. In this phase, we have taken into account the so-called "permanent" and "cyclical" colours. The "permanent" colours are the basis of any chromatic study. They constitute the stable elements of the place, having a durable character, such as the building materials. They are opposed to "cyclical" colours, which are unstable and subject to innumerable temporal, meteorological and light variations, such as the colour of patinas, plants, the sky (etc.).
The second phase consisted of recommending atmospheres adapted to the place, using chromatic ranges, materials and lighting systems that favour the safety and visual comfort of all inhabitants. This method consisted of experimentally constructing chromatic ranges by means of the view, proceeding by variation and multiplication of optical combinations until a visual impression was obtained that conformed to the aesthetic expectations of the project. To design these colour schemes, we used the NCS colours previously surveyed on the site, which we then matched with the paint and material manufacturers' colour charts used for the project. Thus, a visual atmosphere was designed around the spirit of the place, the chosen shades are sublimated by the contribution of contrast around several soft and assertive tones inspired by nature and harmonizing perfectly with the vegetation present on the site. These prescriptions have led to the creation of three chromatic palettes specific to each building in the project, (see figure 2).

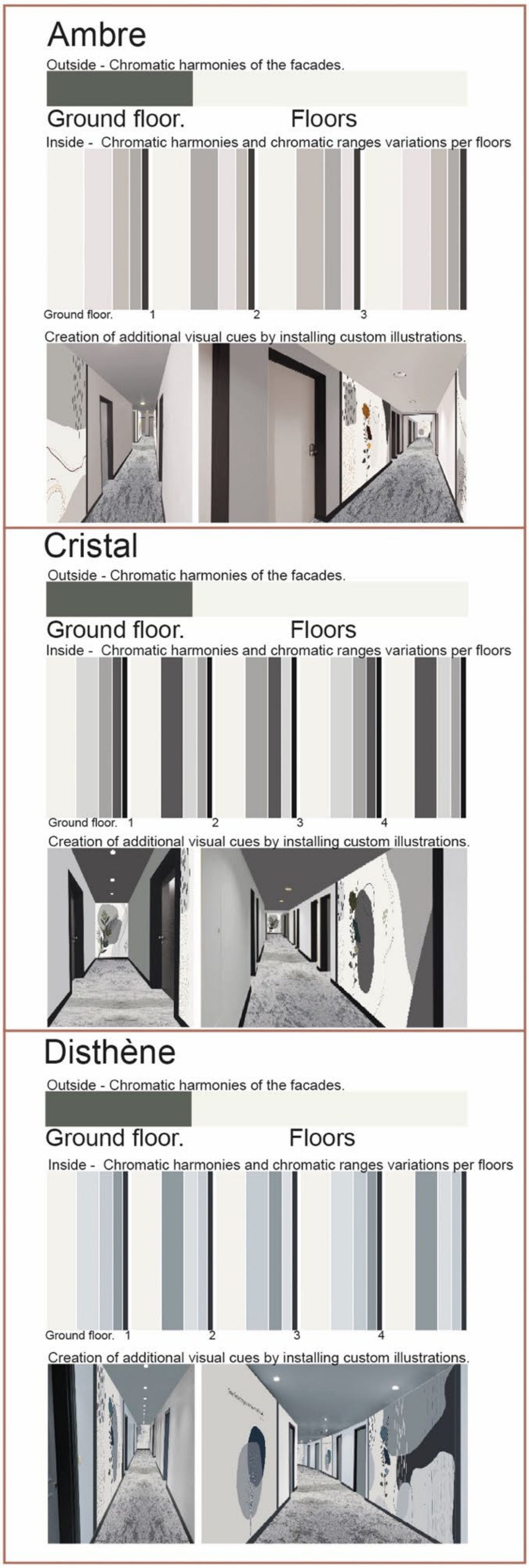


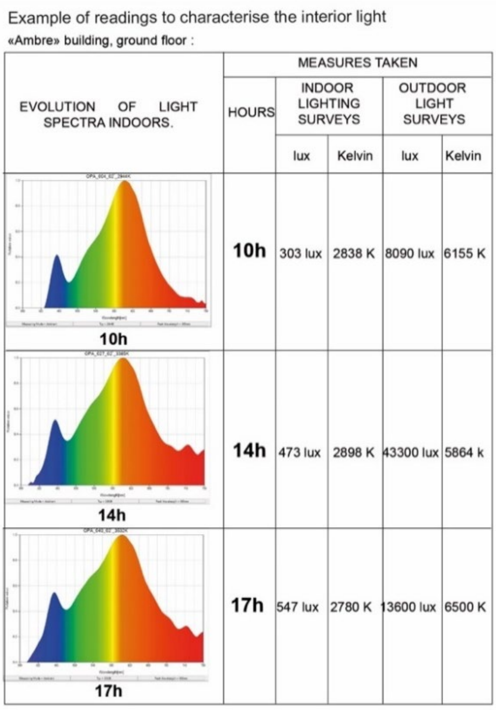
Fig. 2 . Chromatic environment creation.

Inside, the chromatic combinations are composed of five shades, but established on a dominant trichromy (Déribéré, 2014), varying at each level, thus avoiding any visual disturbances caused by a discordant polychromy, and relieving the space of a certain visual monotony recurrent in this type of place. Particular attention was paid to chromatic contrast and luminance values, as contrast sensitivity generally decreases with age and can be even more disturbed when visual pathology is added. For example, a contrast of 70% has been maintained between the various important media so that they can be perceived by a visually impaired person, whose sensitivity to contrast is still operative.
Here, light colours are used for large surfaces and dark colours for small surfaces or accessories in order to allow better discrimination of the elements. The creation of these differentiated harmonies has therefore allowed us to design circulation spaces with chromatic variations for each level, favouring intuitive orientation as well as an efficient and comfortable reading of the chain of movement for all inhabitants. This colour scheme was accompanied by numerous contrasting visual markers, designed for the occasion. The 77 illustrations installed in the residence not only serve as landmarks, but also have the advantage of dynamising and reducing the perception of large landings and long corridors which can be perceived as anxiety-provoking.
Thus, this evidence-based approach to colour and contrast integrated into the design of the environment improves visual awareness of the environment. This approach, which is aimed at older people, visually impaired people and people with dementia, is in line with inclusive design guidelines and supports orientation and wayfinding, as well as the safe performance of daily activities.
Finally, these harmonies were also accompanied by a lighting design. This was studied so that the quantity and quality of light would meet the needs of all inhabitants, as at 55 years of age the amount of light required is 300% higher than at 25 years of age, for an equivalent level of visual performance, (Association française de l'éclairage, 2020). For this reason, we recommended an average of 300 lux at floor level, homogeneous throughout the buildings, using direct and indirect LED lighting with a colour temperature of 3000 Kelvin. Finally, the choice of materials was studied in order to recommend finishes ranging from matte to satin in the entrance halls according to their natural light contribution in order to adapt to each exposure and thus not generate glare or darkness.

Finally, the third phase was the creation of a technical execution file for the project management. This file is based architect and includes normative descriptions as well as graphic documents such as colouring diagrams on plans, lighting system layout diagrams, cross-sections, a details and signage booklet, as well as a material library to ensure the proper implementation and monitoring of the project.

3.4. *Step 3: Feedback*

Finally, following the completion of the works and the installation of the inhabitants, we repeated a series of measurements inside the various common areas. These measurements provided additional information on the relevance and effectiveness of the recommendations made prior to the project. This last observation phase consisted of characterising the light and colour present in the buildings. To do this, we carried out several series of measurements along the movement chain.
First of all, we repeated a referencing of the environment inside the common areas with the help of photographs and chromatic counter-types. These chromatic collections were used to draw up a cartography. Establishing a chromatic representation of a place through a cartography allowed us to produce a qualitative and quantitative restitution of the colours collected in situ, in order to draw up a visual synthesis and to validate the efficiency of the contrasts.
Secondly, we carried out a series of measurements to characterise the lighting environment of the site. The evaluation was carried out at three different times of the day (morning at 10:00, early afternoon at 14:00, late afternoon at 17:30) to measure the light amplitude. In addition, in order to analyse the light distribution of the area, the area was divided into several zones of the site (strategic point of the movement chain).
This series of measurements was carried out using a CRI Luxmeter-Chromameter (Minolta CL-70 F), allowing us to collect all the values composing the light such as its colour temperature; its illuminance; its light spectrum and its colour rendering index, (see figure 3).



Example of readings to characterise the interior light
«Ambre» building, ground floor :

EVOLUTION OF LIGHT SPECTRA INDOORS.	MEASURES TAKEN				
	HOURS	INDOOR LIGHTING SURVEYS		OUTDOOR LIGHT SURVEYS	
		lux	Kelvin	lux	Kelvin
10h	10h	303 lux	2838 K	8090 lux	6155 K
14h	14h	473 lux	2898 K	43300 lux	5864 k
17h	17h	547 lux	2780 K	13600 lux	6500 K

Fig. 3 . Collection of values composing the light of common spaces.

Secondly, we used a video luminance meter, which allowed us to collect the values that make up the light comfort of these spaces, such as luminance, unified glare ratio (UGR), daylight glare index (DGI) and visual comfort probability. In order to analyse the light distribution of the different spaces that make up the residence, the surveys were divided into several zones, consisting of strategic points in the movement chain specifically lit with natural or artificial light. We then chose three periods of the day to carry out the measurements.
This distribution in time makes it possible to analyse the evolution of the amount of light during the day, mainly in the halls and the sharing lounge (common space intended for the creation of sharing workshops between the inhabitants). Also, in order to compare the values between artificial and natural light, we also carried out measurements of the external light, simultaneously with the internal light. These photometric collections were used to draw up a measurement table showing the quantities of light and colour temperatures perceived during the day in different areas of the residence.
Finally, we plotted these data on the Kruithof curve in order to deduce whether the visual environments were considered comfortable or not for the observers, (see figure 4).
Synthesising this information allowed us to produce a qualitative and quantitative restitution of the light present in situ, in order to draw up a visual synthesis and to validate the efficiency and possible nuisances during the day.
Finally, a survey was carried out among the inhabitants in May 2022. The survey was administered by paper questionnaire; residents were asked to share their age, physical condition and the name of their building. The questionnaire consisted firstly of measuring the general satisfaction with the care given to the (interior) environment of the residence and secondly of describing in detail their long-term visual impression of the common spaces. They then assessed their comfort over the course of the month for three specific periods of the day: in the morning, from 8:00 am to 12:00 pm; at noon, from 12:00 pm to 2:00 pm; and in the afternoon, from 2:00 pm to 6:00 pm in different spaces of their residence. For each of these intervals, residents were asked to rate their visual comfort in one of four categories: imperceptible, noticeable, disturbing or intolerable.
Thus, the visual comfort and general appreciation ratings of the residents were compared to the measurements carried out in situ in order to correlate the metric data collected with the visual atmosphere felt.

4. Result

The different phases of surveys and analyses contributed to demonstrate in a quantitative and normative way how the place could be perceived by the inhabitants (INSEE, 2017).

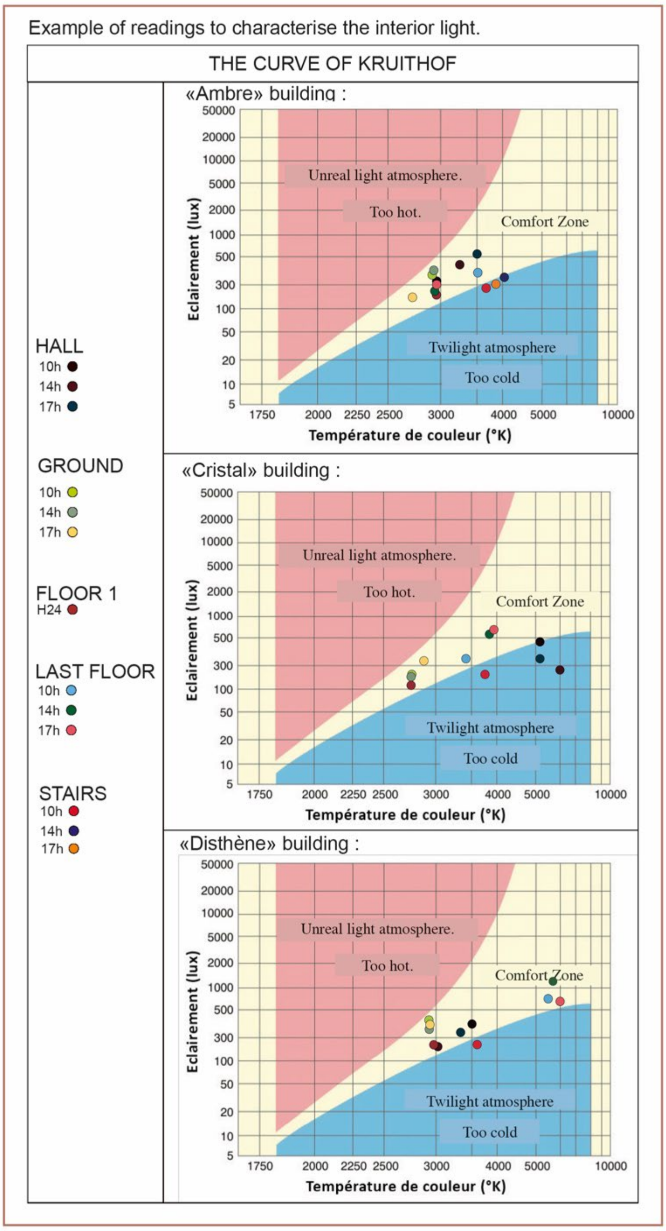


Fig. 4 . Visual comfort control with the Kruithof curve.

The interpretation of the results obtained at the time of delivery enabled us to validate the efficiency of the recommendations established thanks to the analysis protocol carried out before the project, beyond the consideration of the standards in force, this one calling upon an experimental construction method (Pfeiffer, 1966), taking into account several factors intrinsic to the project and which will be reiterated on the projects to come:
- The analysis of the characterisation of colour and light on the site.
- The spirit and visual coherence of the project location.
- An efficient chain of movement.
- The comfort of use and appreciation of the spaces for all inhabitants.

We can conclude that this research-creation protocol and the expertise carried out around the chromatic and luminous characterisation within the circulation spaces was validated by the feedback established in the last phase. Indeed, the measurements taken in situ correlated with the feelings of the inhabitants validated the hypothesis that this approach generates more visual reference points and comfort of use for all the inhabitants. Moreover, these results were compared to other data collected on a sample of the developer's previous real estate projects that did not benefit from this creation protocol and did not have such good results; this confirmed the fact that this new design approach is now a health and social necessity.

5. Discussion

The issue of lighting and colour in collective housing is quite complex, as designers' preferences vary greatly according to both objective and quantifiable conditions (economy, standardisation of practices, specific needs related to disabled people, etc.) and socio-cultural and subjective conditions (preference for a particular colour scheme, type of luminaire, type of covering, etc.).
As a result, and in the absence of standards directly related to these semi-private spaces, architects tend to use very neutral or even monotonous colours and materials, and struggle to install sufficiently efficient, comfortable and aesthetic lighting in common spaces. With this study, we are beginning to awaken designers to the challenges of colour and light. Because together, beyond their simple aesthetic contribution, they make circulation safe and efficient while allowing the inhabitants to plunge into singular universes where the atmosphere becomes a factor of well-being and cohesion.

6. Conclusion

In the coming years, a larger comparative study will complete the research-creation protocol studied in this article. This comparative study will take into account the values obtained in a large sample of old residences and those that are being built from this protocol, and will be completed by an interview with the inhabitants asking them about their perception of the place and based on a scale of sensations. This study will allow the property developer to ensure the efficiency of its approaches and to continue to design in a systematic and sustainable way visual environments better adapted to human physiological needs by proving the validity of qualitative approaches in terms of the design of light and colour within its property programmes.

7. Acknowledgements

I am grateful to the LAPLACE Laboratory of the Paul Sabatier University in Toulouse, France, which made the experiment possible by providing tools. I also thank the company SOBRIM for allowing me to carry out this study and for their interest in the results. Finally, I thank them for their willingness to enhance and develop their academic research within their future real estate programmes through the HARANAM approach.

8. Conflict of interest declaration

No conflict of interest.

9. Funding source declaration

Without funding.

10. Short biography of the authors

Lorrain Caumon - Is a colour designer and an expert in inclusive space design and colour engineering. She is currently a CIFRE doctoral student in the LAPLACE and LARA-SEPPIA laboratory at the University of Toulouse (France). Since 2019, she holds a master's degree in creation, research and innovation in colour (ISCID, France) and is currently a colour designer specialising in inclusive space design within the company SOBRIM. Her research focuses on the interaction between colour design and lighting sciences, with the aim of promoting comfort and well-being in collective housing.

Georges Zissis - PhD, is a full Professor and Director of "Light & Matter" research group of LAPLACE (Toulouse 3 University, France). His primary area of work is in the field of light sources science and technology

Céline Caumon - PhD and Prof. at the University of Toulouse-Jean Jaurès. With the initiative of the creation of the Institute Color Image Design (ISCID, France), she participates in the development of colordesign in other scientific disciplines and in the socioeconomic world.

References

Association française de l'éclairage (2020) *FICHES PRATIQUES : ÉCLAIRAGE DANS LES COLLECTIVITÉS.* Association française de l'éclairage, p. 56. Available at: http://www.afe-eclairage.fr/.

Bay, B. and Fayolle, C. (eds) (2020) *Couleur et soin*. *Couleur et soin*, Paris: Les presses du réel.

Brutel, C. (2002) 'La population de la France métropolitaine en 2050 : un vieillissement inéluctable.', (N° 355-356), p. 16.

Damelincourt, J.-J. *et al.* (2010) *Éclairage d'intérieur et ambiances visuelles*. Paris: Éd. Tec & doc (Optique et vision).

Déribéré, M. (2014) *La couleur*. 12e éd. Paris: Presses universitaires de France (Que sais-je ?, n° 220).

Henri Albertini *et al.* (2018) *Logement − Tableaux de l'économie française | Insee*. (Insee référénce). Available at: https://www.insee.fr/fr/statistiques/3303460?sommaire=3353488 (Accessed: 29 March 2022).

INSEE (2017) *Les conditions de logement en France.* Available at: https://www.insee.fr/fr/statistiques/2586040?sommaire=2586377.

Kubiak, Y. (2012) *Personnes âgées dépendantes : le maintien à domicile, solution privilégiée mais exigeante - Economie Lorraine | Insee*. 289. Available at: https://www.insee.fr/fr/statistiques/1292722 (Accessed: 28 March 2022).

Lenclos, J.-P. and Lenclos, D. (2016) *Couleurs de la France: géographie de la couleur*. Le Moniteur.

Mormiche, P. (2001) 'L'enquête HID de l'INSEE', *Gerontologie et societe*, 2499(4), pp. 57–77.

Mudri, L. (2002) 'Luminous ambience, quantitative/qualitative data and subjective response', p. 12.

Pfeiffer, H. (1966) *L'harmonie des couleurs. Cours théorique et pratique.* 3ème édition. Paris: Dunod.

SOBRIM - HARANAM (no date) *Le pôle recherche et développement - Sobrim*, *https://sobrim-immobilier.com/*. Available at: https://sobrim-immobilier.com/haranam/pole-recherche-et-developpement/ (Accessed: 18 January 2022).

Colour and emotion: the use of the colours of Lüscher test in the artistic field

Giorgia Flaviani[1], Alice Plutino[1], Alessandro Rizzi[1]

[1] Department of Computer Science, Università degli Studi di Milano, Milano, Italy

Corresponding author: Alice Plutino (alice.plutino@unimi.it)

ABSTRACT

The Lüscher colour test was created by the Swiss psychologist Max Lüscher in 1949 and consists of several coloured patches that can be used to assess the patient's psychological state and profile. The main advantage of this test is its high usability and trustability.

After a preliminary analysis of using Lüscher colours, we set up a first perceptive test asking 20 subjects to associate adjectives with Lüscher's colours freely. This first test aims at defining if the basic colour terms defined by Lüscher and used to create psychological assessments are coherent and consistent in a free term-association test.

After this first perceptive test, we integrated Lüscher's basic colours with the ones used by Kandinskij, an artist who Lüscher's colour theories have strongly influenced. In this second test, we considered both Lüscher and Kandinskij basic colours. We asked 49 people to associate the colours with specific terms derived from the Lüscher theory, Kandinskij system and the first test.

From the analysis of these two experiments, it has been possible to demonstrate a strong coherence of specific colour-terms associations, which are consistent with the introduction of controlled colour shifts, while other colour-terms associations present a higher variability.

KEYWORDS Lüscher colours, Kandinskij, colour and culture, colour and art

RECEIVED 30/12/2022; **REVISED** 17/03/2023; **ACCEPTED** 06/07/2023

---

1. Introduction

The colour test was created by the Swiss psychologist Max Lüscher in 1949 and consists of the use of 8 coloured patches that should be placed on a scale of subjective preference (Lüscher, 1976). This scale allows the definition of a psychological profile of the tester. The subjective characteristic of Lüscher's test, the choice of favourite and rejected colours, and the psychic effect produced by the vision of different colours can also be found in the arts (Itten, 1970). A correspondence was sought in the colour theories of artists in the visual and cinematographic field, finding indirect conformity in contemporary painters like Vasilij Kandinskij and Yves Klein; and directors like Derek Jarman and Valerio Mieli (Bora G. et al., 2010a). The biggest match was found in Kandinskij's *Concerning the spiritual in art*, where some of Kandinskij's paints have been identified to record the work's emotional impact on the observer (Kandinsky, 2012). We can divide the work into two sequential stages or experiments as follows.

In the first testing phase, 20 people did the Lüscher test and were asked to make a free association of adjectives to Lüscher's colours. This test aimed at answering the research question: *Are Lüsher's basic colour terms conform with the perceived emotions/sensations?* From the data obtained, we can better define the correspondence of Lüsher's colour theory to reality. In fact, for example, blue was associated with the term peace and calm, as Lüscher said, and as also reported in a large body of scientific literature (Valdez & Mehrabian,1994).

From this point, considering the strong influence of Lüscher's colour theory in art (e.g., Kandinskij, Klein, Mieli), we conducted a second perceptive test. We asked 49 people to associate specific colour terms derived from the first experiment, Lüscher's colour theory and Kandinskij's theory, with colours extracted from Lüscher's test and Kandinskij's works of art. The aim of this second experiment is to answer the research question: *How much (perceptually) consistent is Lüsher's test?*

1.1. *Lüscher colour test and its influence on art*

The colour test by Max Lüscher is composed of eight coloured patches; each colour is associated with a particular meaning. This test's advantages are the administration speeds, universal validity and good reliability. Eight coloured cards are used, which the tester sets to scale of preference. From the colour, they prefer the less appreciated. This scale is the first step for interpreting the test result, given through the consultation of the tables to analyze the functions. The colour does not change based on meaning, but the position in the scale altered the interpretation of the tester's personality. Lüscher's colours theory is based on the psychophysics effect produced by the sight of a specific colour.

These eight colours are divided into primary colours (blue, yellow, red and green) and additional colours (purple, brown, grey, and black). The primary colours usually stay at the beginning of the preference scale. If this does not happen, it can indicate psychological and physical stress in the patient. Psychologists and psychiatrists use this test to help highlight the tester's personality (O'connor, 2011; French, C. A. et al. (1972)).

State of the art on the use of Lüscher's test was carried out and allowed us to analyze the links between the colours of the psychological examination, with the colours used by artists to arouse the same emotions as those defined by Lüscher.

The conceptual framework for colors's interpretations was found by Lüscher in German Romantic theory, in Goethe's Farbenlehre (Theory of Colours) of 1810. At one point in the first German edition of his book, published on the anniversary of Goethe's birth in 1949, Lüscher even introduced the ancient and medieval notion of the correspondence of the four humours and the four elements, with one of the sets of colours attributed to them. Goethe and his fellow-poet Friedrich Schiller had been working along similar lines at the close of the eighteenth century. The Luscher system certainly rests on what seems to be a universal urge to attribute affective characters to colours, and it must be taken at the very least as an important modern manifestation of that urge (John Gage,1999)

Some correspondence can be found in the theories about colours by some artists in pictorial and cinematography (e.g., Derek Jarman and Valerio Mieli), as well as in contemporary painters (e.g., Vasilij Kandinskij and Yves Klein). In this contest one of the most interesting correspondences can be found in Kandinskij's work *Concerning the spiritual in art (1910), that includes perhaps the most wide-ranging body of colour-ideas for modern artists.*

Vasilij Kandinskij is considered the father and theorist of abstract painting. For him, colours are the key to interpreting his paintings, and he thinks there is a link between art and the spiritual dimension. Kandinskij describes colours as sensations and feelings. Kandinskij's paintings are a striking example of Lüscher's theory because they are abstract and predominate colour and shape, whereas the narration it's only suggested and subjective. Lüscher's influence on Kandinskij, the correspondences and differences in their colour theories, and the universal recognition of their works, have been the basic elements of this study to assess the consistency of Lüscher's colours.

2. Materials and Methods

2.1. *Basic colour terms*

The Lüscher's colours are divided into primary colours (red, green, yellow and blue) and auxiliary colours (purple, brown, grey and black). As stated in *Il Test dei colori* by Max Lüscher, blue represents peace, calm, contemplation, and calming effect on the Central Nervous System. The body starts to relax, and psychologically blue increases vulnerability, tranquillity and the satisfaction of being in peace.

Green represents elastic tension, work, perseverance, tenacity, constancy and resistance to changes. Its emotional content is pride.

The test's red presents a point of yellow that forms orange, representing a physiological condition of energy consumption. Red speeds up blood pressure and increases the respiratory rate. Red is the expression of the life force and nervous activity. Red is impulsive, desire to win, active action, impact and willpower. Its emotional content is desire.

Yellow is the brightest colour of the test and means light and happiness. Yellow increases blood pressure, frequency of pulsations and breathing, similar to red. However, it is less stable in this action. Its main characteristics are brilliance, reflexivity, radiant qualities, and joy. Yellow express uninhibited affectivity and opening. It corresponds symbolically to the pleasant heat of the sun.

Purple is a mix of blue and red. It links the impulsive conquest of red with the gentle surrender of blue, representing identification. Purple can mean intimacy and erotic fusion or lead to an intuitive and sensitive understanding. The attitude of desire satisfaction can also mean identification as an inability to differentiate or an unresolved sway, which can both create irresponsibility.

The brown of the test is a dark yellow-red. Brown stays in the indifference zone of the colour scale. The extroverted vitality of red is reduced by its darkness. With brown, the vitality becomes passive, sensory and receptive.

The Lüscher's grey is neutral, neither subject nor object, neither inner nor outer, neither tension nor relaxation. With its unique no-involvement characteristic, grey contains an accentuated hiding element. Grey is not an occupied territory but a border as no man's land.

Black is a negation of colour. Black negation represents renunciation, complete capitulation, or abandonment and strongly influences the choice of other colours, refounding its character. The "no", in opposition to the "yes" of white, represents the absolute limit beyond which nothing is left.

Considering now, Kandinskij's theories expressed in *Concerning the spiritual in art,* colours are often intended as in movement and relation to shapes. If we extract the given meaning of each colour, blue is related to the sky. Blue represents depth and peace with a divine purpose. In Kandinskij's theory, also green represents peace and relaxation, but in a satisfying way, more terrain if compared with blue. Red is intended as the colour of vitality and agitation and is considered less superficial than yellow. Yellow is considered the colour of youth and excitement, which can tend to madness.

Kandinskij considers purple like a cool red, which is sad and soft. Brown is the colour of the absence of dynamism and is obtuse and tough. Similarly, grey is the colour of steadiness and restrictions. In conclusion, black is a non-colour, a way to turn off all the other colours.

We can find some correspondences and differences by considering this general analysis of Lüscher's and Kandinskij's colour theories. First, we must assume that Lüscher refers to specific colour shades, while Kandinskij expresses views on pure colours, which are often considered in relation to the space or each other. This difference reflects on the associated colour terms, which present slight variations, especially for blue, yellow and green. In particular, green is the colour which shows the highest differences since, for Lüscher, it is linked to tension and dynamism, while for Kandinskij is linked to relaxation and peace.

Nevertheless, the similarities between words and meanings are noticeable. Blue is for both related to a celestial elevation, infinity, divine and deepness. Red is a vital and dynamic colour, as well as yellow. Purple is considered sensual and erotic, brown is linked to inhibition, grey to neutrality and black to denial.

The similarities and coherence in some colour meaning is extremely relevant and has been the base for our experiments.

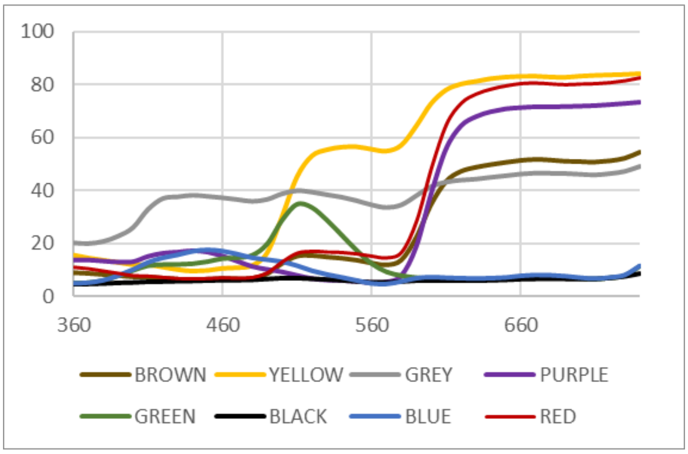


Fig. 1 Reflectance spectra of Astrolabio's colour patches.

2.2. *Colour analysis and extraction*

The colour patches used in this experiment are from Lüscher's *Il test dei colori* edited by Astrolabio. The coloured patches included in the book have been analyzed with a CM2600d spectrophotometer by Konica Minolta, and the data have been analyzed with the software Spectra Magic Nx Pro (see Fig. 1).

The extracted reflectance spectra have been converted in CIE XYZ values (2° standard observer, D65 standard illuminant) and then in sRGB colour space (see Table 1). The original patches from the book were used in the first experiment (Section 3.1), and in the second experiment (Section 3.2) have been used the derived digital patches in sRGB (Oleari C., 2008).

In the second perceptual experiment, the digital reconstruction of Lüscher's colours has been combined with the primary and auxiliary colours digitally extracted from three of Kandinskij's works:

- Several Circles,1926, New York, Guggenheim Museum.

- Colour Study. Squares with Concentric Circles, 1913, Monaco di Baviera, The Städtische Galerie im Lenbachhaus.

- Composition VIII,1923, New York, Guggenheim Museum.

The sRGB coordinates of the digital versions of those paintings are reported in Tab. 1. A similar experiment has been presented in (Malfatti, M., 2014), but in that case authors focused also on the relation shape-colour.

3. Experiment

3.1. *Free colour terms association*

In the first perceptual experiment, we asked 20 people (ages between 5 and 81) to freely associate 8 colour terms to each basic Lüscher's colours. The test was performed in person using the 8 colour patches from the book *Il test dei colori*. To do not influence the participant, we asked to each one: "*Senza fretta, ma istintivamente dì i primi 2 aggettivi che ti sembrano emozionalmente legati a questo colore"* (Without any rush but instinctively say the first 2 adjectives that seem emotionally linked to this colour).

The adjectives from the participants have been recorded and ordered depending on their frequency. Subsequently, we compared the adjectives expressed by the subjects with Lüscher's terms associated with each colour (see Table 2).

	RED	GREEN	BLUE	YELLOW	PURPLE	BROWN	GREY	BLACK
Astrolabio colour patches								
R	211,4	-78,35	65,66	229,87	198,78	174,71	170,71	65,5
G	106,27	131,4	75,97	195,15	56,4	102,55	163,39	69,8
B	66,71	106,86	118,88	69,8	114,18	69,83	169,55	71,59
Several Circles,1926, New York, Guggenheim Museum								
R	179		25	205	177	93	186	18
G	25		48	195	133	55	182	22
B	51		98	71	152	40	207	27
Colour Study. Squares with Concentric Circles, 1913, Monaco di Baviera, The Städtische Galerie im Lenbachhaus								
R	237	79	51	239	116	156	90	69
G	64	145	73	196	106	88	91	59
B	16	73	154	23	148	64	92	56
Composition VIII,1923, New York, Guggenheim Museum								
R	182	85	91	227	130	148	156	34
G	29	125	143	183	109	89	156	32
B	5	83	162	68	156	30	127	33

Tab. 1 sRGB coordinates derived from Astrolabio's reflectance spectra and from the official photographs of Kandinskij's paintings.

Colours	Lüscher	Kandinskji
Blue	Serenity, peace, infinity	Depth, intensity, peace
Red	Intense excitement	Envelop, vital, restless
Yellow	Alive, light, cheerfulness	Madness, excitement
Green	Elastic tension, will, perseverance, firmness, constancy, resistance, pride, superiority	Peace, calm, relaxing, beneficial for human.
Purple	Identification, eroticism, desire, irresponsibility, charm	Sensual, soft, sad
Brown	Indifferent, inhibited	Inhibition
Grey	Nothingness, neutrality	Still, hopeless, strict
Black	Colour denial, end, waiver, abandonment	Dryness, eternal silence, non-colour

Tab. 2 Lüscher and Kandinskji terms associated to each analyzed color.

3.2. *Defined colour terms association*

In the second perceptual experiment, we asked 49 people to freely associate 11 colour terms derived from Lüscher's colour theory, Kandjnskij's works and the first experiment to each basic colour derived from Kandjnskij's selected paintings. The test was performed online using Google Forms, showing the participants a colour-term combination and asking them to assess the appropriateness of the association. For example, for the green from the painting *Composition VIII* we asked, "On a scale of one to ten, how much *determination* does it give you?" or "On a scale of zero to ten, how much *vitality* does it give you?" or "On a scale of zero to ten how much *relaxing* does it give you?". Testers had to assign a number, between zero and ten, to each question. The answers were collected in graphs, and the results were analyzed.

4. Results

4.1. *Free colour terms association*

The results of the first perceptual experiment are:

BLUE: deep (15%), peace (15%), calm (15%), nocturnal (10%), intense (10%), infinity (10%).

YELLOW: sunny (35%), cheerfulness (15%), summery (15%), bright (15%), tenderness (10%).

GREEN: vital (25%), lively (10%), maritime (10%), hope (10%), brilliant (10%), thoughtless (10%), brightness (10%).

RED: warm (20%), spring (10%), happy (10%), hot (10%), playful (10%), enjoy (10%).

PURPLE: cheerfulness (20%), feminine (20%), happiness (15%), lively (15%), wellness (10%), joy (10%).

BROWN: sad (10%), warm (10%), wet (10%), tacky (10%)

GREY: tranquility (15%), boring (10%), monotony (10%), clean (10%), apathetic (10%).

BLACK: dark (20%), elegance (10%), death (10%), sadness (10%), neutral (10%), loss (10%), mystery (10%), charm (10%), empathic (10%).

4.2. *Defined colour terms association*

Here we report some of the most significant results from the second perceptual analysis.

For this second experiment we chose to report a frequency major than 10%. The terms we considered are derived from the correspondence of the sensation evoked by each

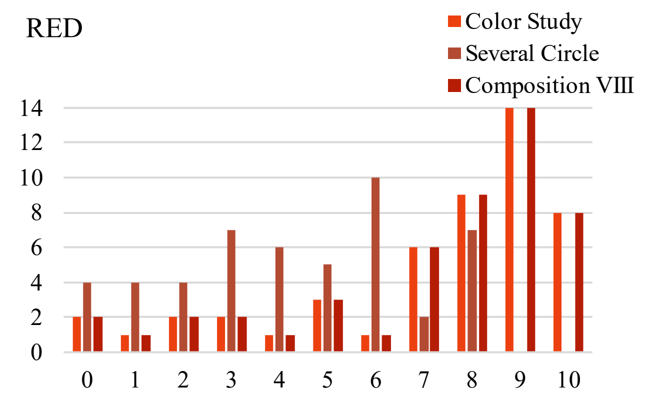


Fig. 2 Evaluation of the excitement triggered by the reds from three Kandjnskij's works of art.

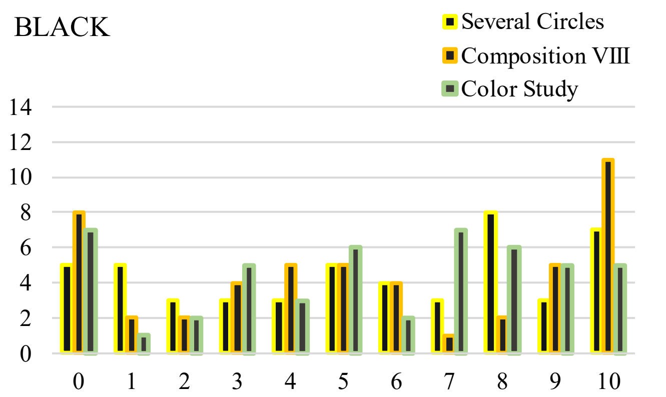


Fig. 3 Evaluation of the negativity triggered by the blacks from three Kandjnskij's works of art.

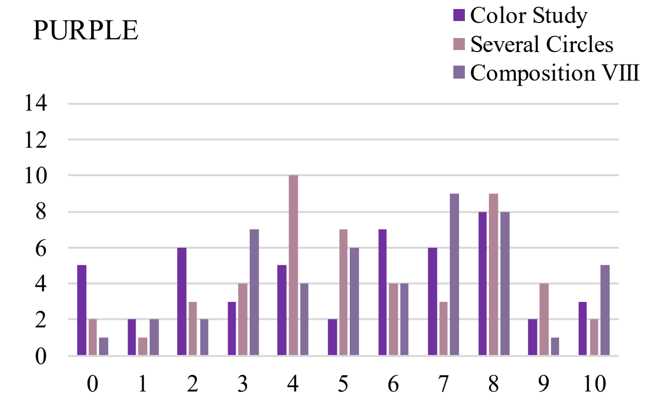


Fig. 4 Evaluation of the attraction triggered by the purples from three Kandjnskij's works of art.

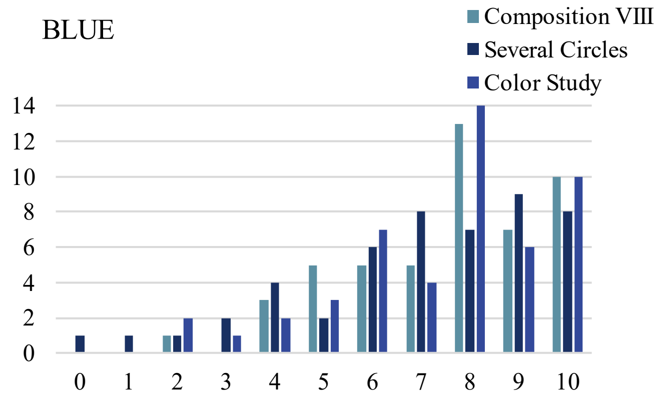


Fig. 5 Evaluation of the serenity triggered by the blues from three Kandjnskij's works of art.

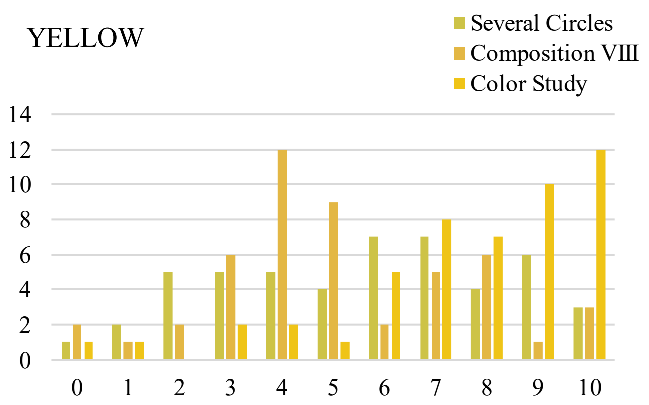


Fig. 6 Evaluation of the joy triggered by the yellows from three Kandjnskij's works of art.

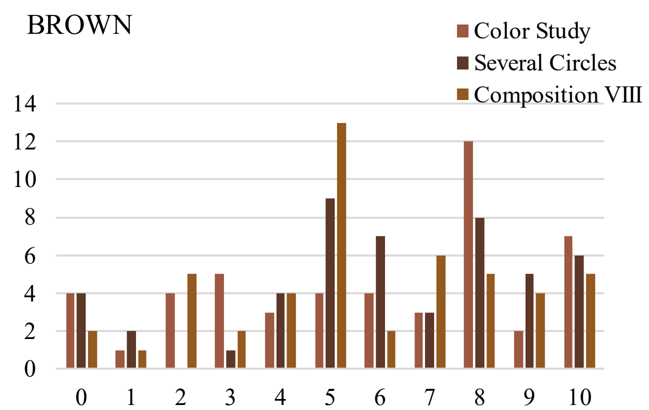


Fig. 7 Evaluation of the disregard triggered by the browns from three Kandjnskij's works of art.

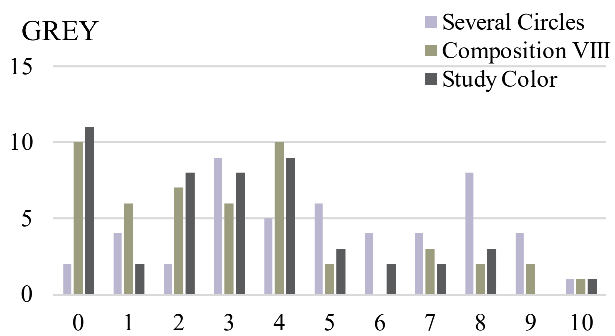


Fig. 8 Evaluation of the involvement triggered by the greys from three Kandjnskij's works of art.

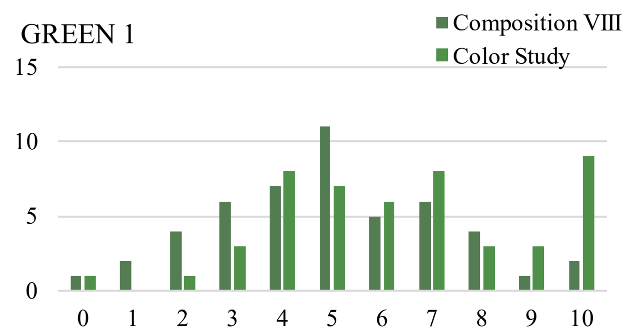


Fig. 9 Evaluation of the vitality (testers) triggered by the greens from three Kandjnskij's works of art.

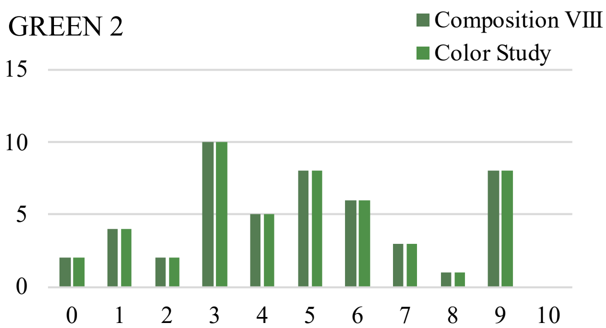


Fig. 10 Evaluation of the determination (Lüscher) triggered by the greens from three Kandjnskij's works of art.

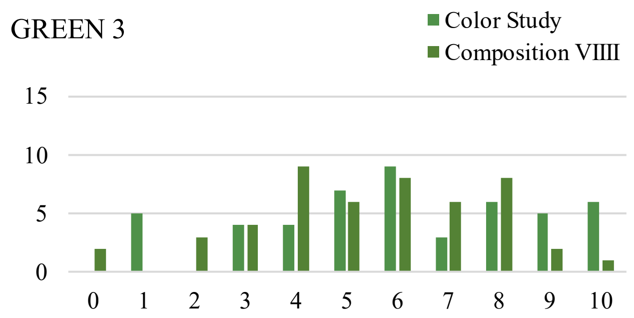


Fig. 11 Evaluation of the relaxing (Kandinskij) triggered by the greens from three Kandjnskij's works of art.

colour between Lüscher's colour theory, Kandinskij's theory, and the results of the first experiment given by 20 testers for each color.

For the red colour, we have considered the feeling of excitement that the sight of this colour can provoked (see Fig.2).

For the black colour, we have considered the feeling of negativity that the sight of this colour can cause (see Fig. 3).

For the purple colour, we have considered the state of attraction that the sight of this colour can provoke (see Fig. 4).

For the blue colour, we have considered the feeling of serenity that the sight of this colour can cause (see Fig. 5).

For the yellow colour, we have considered the state of joy that the sight of this color can provoke (see Fig. 6).

For the brown colour, we have considered the feeling of disregard that the sight of this colour can provoke (see Fig. 7).

For the grey colour, we have investigated the state of involvement that the sight of this colour can provoke. Which is the opposite feeling provoked by the sight of this colour mentioned in the three theories (see Fig. 8).

For green colour, there is an inconsistency with the association of terms for this colour between Lüscher's theory, Kandindkij's theory and the terms associated by the testers in the first experiment. We therefore studied three types of feelings caused by the sight of this colour (see Fig. 9, Fig. 10 and Fig. 11).

For Lüscher' theory we investigated the sensation of determination, for Kandinskij's theory we chose the state of relaxing, and from the results of the first experiment we considered the sensation of vitality.

4.2.1 Additional results

In Section 4.2 we reported the color terms association with a frequency higher than the 10%. For completeness here we list briefly all the results above the threshold concerning the second experiment (i.e., defined color terms associations).

RED:

"On a scale from zero to ten how much excitement does it give you?" 7.46% of the testers gave zero, 4.75% gave one, 5.42 % gave two, 6.79% gave three, 7.46% gave four, 17% gave five, 16.3% gave six, 12.2% gave seven, 17% gave eight , 12.2% gave nine and 6.79% gave ten.

BLUE:

"On a scale from zero to ten how much serenity does it give you?" 0.67% of the testers gave zero , 0.67% gave one, 2.71% gave two, 2.04% gave three, 6.12 % gave four, 6.79% gave five, 12.2% gave six, 11.5% gave seven, 23.1 % gave eight , 14.9% gave nine and 19.04% gave ten.

YELLOW:

"On a scale from zero to ten how much joy does it give you?" 2.7% of the testers gave zero, 2.7% gave one, 4.75% gave two, 8.83% gave three, 12.9% gave four, 9.51% gave five, 9.51% gave six, 13.5% gave seven, 11.5% gave eight, 11.5% gave nine and 12.2% gave ten.

"On a scale from zero to ten how much joy does it give you?" 2.7% of the testers gave zero, 2.7% gave one, 4.75% gave two, 8.83% gave three, 12.9% gave four, 9.51% gave five, 9.51% gave six, 13.5% gave seven, 11.5% gave eight , 11.5% gave nine and 12.2% gave ten.

PURPLE:

"On a scale from zero to ten how much attraction does it give you?" 5.42% of the testers gave zero , 3.38% gave one, 7.46% gave two, 9.51% gave three, 12.9% gave four, 10.2% gave five, 10.2% gave six, 12.2% gave seven, 17% gave eight , 4.75% gave nine and 7.46% gave ten.

BROWN:

"On a scale from zero to ten how much disregard does it give you?" 6.79% of the testers gave zero , 2.71% gave one, 6.12% gave two, 5.42% gave three, 7.46% gave four, 17.67% gave five, 17% gave six, 8.16% gave seven, 17% gave eight , 7.46% gave nine and 12.2% gave ten.

GRAY:

Remembering that the opposite meaning was used for grey. "On a scale from zero to ten how much involvement does it give you?". 15.6% of the testers gave zero , 6.79% gave one, 11.5% gave two, 15.6% gave three, 16.3% gave four, 7.46% gave five, 4.08% gave six, 6.12% gave seven, 8.83% gave eight , 4.08% gave nine and 2.04% gave ten.

BLACK:

"On a scale from zero to ten how much negativity does it give you?" 13.6% of the testers gave zero , 5.42% gave one, 4.75% gave two, 8.16% gave three, 7.46% gave four, 10.88% gave five, 6.79% gave six, 7.46% gave seven, 10.88% gave eight, 8.83% gave nine and 15.6% gave ten.

GREEN:

Three sensations were considered for the colour green. This colour is only present in two paintings. The first sensation investigated comes from Luscher's theory. "On a scale from zero to ten how much determination does it give you?" 2.04% of the testers gave zero , 4.08% gave one, 5.1% gave two, 13.26% gave three, 12.2% gave four, 12.2% gave five, 13.26% gave six, 10.2% gave seven, 7.14% gave eight, 14.28% gave nine and 6.12% gave ten.

The second sensation investigated comes from Kandinskij's theory. On average for the colour green to the question "On a scale from zero to ten how much relax does it give you?" 2.04% of the testers gave zero , 5.10% gave one, 3.06% gave two, 8.16% gave three, 13.26% gave four, 13.26% gave five, 17.34% gave six, 9.18% gave seven, 14.28% gave eight , 17.14% gave nine and 7.14% gave ten. The third sensation investigated comes from tester's adjectives "On a scale from zero to ten how much vitality does it give you?" 2.04% of the testers gave zero , 2.04% gave one, 5.1% gave two, 9.18% gave three, 15.3% gave four, 18.3% gave five, 11.22% gave six, 14.28% gave seven, 7.14% gave eight , 4.08% gave nine and 11.2% gave ten.

5. Discussion and conclusion

Considering the first test's results reported in Section 4.1 there is a strong variance in the colour-terms associations. Often, a cognitive term association (e.g., yellow – sunny; red – hot; green – hope) underlines the influence of cognitive functions regardless of emotional associations; this result can be explained by the nonlinearity of the color-emotion association as shown in the literature (Bortolotti et al., 2022; Jonauskaite et al., 2021). Comparing these results with the colour terms used by Lüscher and Kandinskij, there is a strong accordance for specific colours while discording others (see Table 2). The blue colour is the one which presents the strongest accordance with Lüscher and Kandinskij. Among the most frequent colour terms, we have peace, infinity and intensity, as theorized by the two authors. Also, for the yellow, we have accordance among the participants and Lüscher's and Kandinskij's theories (e.g., cheerfulness and light). Considering the red, Lüscher associates to this colour an intense excitement, which can correlate with the terms happy, playful, and enjoy expressed by the test's participants. Nevertheless, this association is not completely coherent with Lüscher's theory. The green presents the most surprising results since the subjects did not associate terms related to perseverance, resistance, and tension. The test's subjects seem to agree more with Kandinskij's definitions. In fact, terms like alive, hope, and brightness can correlate with the painter's concepts of peace and relaxation. Considering the auxiliary colours (purple, brown, grey and black), black we have correspondence with the Lüscher’s theory, and the adjectives given by the testers. For Lüscher we have the concept of the end and the testers give “death”, whereas with the Kandinskij’s theory and adjectives given by the testers there is no link. For the grey colour we didn’t find a correspondence, for Lüscher grey is linked with the concept of neutrality, for Kandinskij is linked with the concept of steadiness and for testers is linked with the concept of tranquility.For the purple we have accordance among the participants and Luscher’s and Kandinskij’s theories. Participants associated this color with the concept of feminine, for Luscher’s is linked with the concept of erotism, desire and charm, and for Kandinskij’s with the sensuality. These free concepts are linked. For brown there is no correspondence with the meaning given by Kandinskij or Lüscher and the adjectives given by the testers. In fact, it is the colour that provided the greatest variety of adjectives from testers.

The second perceptual test was performed to avoid the cognitive term's associations that came out in the first test and to investigate further the consistency of Lüscher's (and Kandinskij's) colour theory. The excitement associated with Lüscher to red is also confirmed by the reds extracted from Kandinskij's paintings. This colour also triggers excitement in different shades and is extracted from other contexts. This trend can also be noted for blue, which triggers serenity, and yellow, which triggers joy (also if to a lower extent for the colour extracted from Composition VIII). Considering the greens, the shade from the Colour study triggers vitality and determination, while the one from Composition VIII does not correlate well with Lüscher's terms. This disagreement between Lüscher's colour terms and the greens extracted from the paintings can identify a higher sensitivity of the subjects in green shade variations. This means that a change in the shade of green affects the subjects more than a change in red, yellow or blue. Brown triggers disregard in an average way, and grey does not trigger involvement (confirming Lüscher's theory). In conclusion, black triggers negativity just partially in Composition VIII.

The two perceptual tests presented in this paper helped us to determine that Lüscher's basic colour terms conform with the generated sensations to a greater extent for the primary colours (green excluded). Nevertheless, a further investigation that does not include the possibility of making cognitive associations will be necessary.

The experiments showed in this paper can be potentially affected by cultural factors such as symbolism associated to certain colors.

The perceptual consistency of the Lüscher test has been confirmed just for some colours (blue, red, yellow and grey), while for other colours (like green), the variation in shade causes a strong variation in meaning and associated emotions.

6. Conflict of interest declaration

Authors declare no conflict of interest.

7. Funding source declaration

The authors received no specific funding for this work.

8. Acknowledgment

If applicable, acknowledgement can be placed here.

9. Short biography of the authors

Giorgia Flaviani – She obtain a bachelor's degree in Cultural Heritage Conservation Science at the University of Milan (Italy). She performed bachelor's degree thesis in collaboration with MIPS Lab concerning with the use of the colours of Lüscher test in the artistic field.

Alice Plutino – She obtained a PhD in Computer Science at Università degli Studi di Milano (2021), where now is Research Fellow. Her research interests are Colour Science, Colourimetry, Image Enhancement, Image Digitization and Archiving, with a particular interest in Cultural Heritage applications. She is author of a book and of several journal and conference papers of national and international relevance. She is Adjunct professor at Università degli Studi di Milano and Centro Sperimentale di Cinematografia, teaching digital film restoration and digital media conservation. She is member of the Italian colour group (Gruppo del Coloure), deputy editor of the Colour Culture and Science Journal (CCSJ) and vice-coordinator of Division 1 and Division 8 of NC CIE Italy.

Alessandro Rizzi - He is Full Professor at the Department of Computer Science at the University of Milano (Italy), teaching Multimedia, Colourimetry and Film restoration. He is doing research since 1990 in the field of digital imaging with a particular interest on colour, visualization, photography, HDR, VR and on the perceptual issues related to digital imaging, interfaces and lighting. He is the head of the MIPS Lab at the Department of Computer Science. He has been one of the founders of the Italian Colour Group, Secretary of CIE Division 8, IS\&T Fellow and Vice President. In 2015 he received the Davies medal from the Royal Photographic Society. He is co-chair of the IS&T Conference "Colour Imaging: Displaying, Processing, Hardcopy and Applications", Topical Editor for "Applied Colour Science" of the Journal of Optical Society of America A, Associate Editor of Journal of Electronic Imaging, member of several program committees and author of about 400 scientific works.

Licensing terms

References

Bora G., Ficcadori G., (2010a*), I Luoghi dell'arte Vol.6*, Electa Scuola.

Bortolotti, A., Cannito, L., Anzani, S., Rossi, M., & Palumbo, R. (2022), About the influence of color perceived lightness on psychological functions, *Cultura e Scienza del Colore-Color Culture and Science*, 14(01), pp.112-122.

French, C. A., Alexander, A. B. (1972),The Luscher Color Test: An Investigation of Validity and Underlying Assumptions, *Journal of Personality Assessment*, pp. 361-365, DOI: 10.1080/00223891.1972.10119772

Itten, J. (1970), *The elements of color (Vol. 4),* John Wiley & Sons.

Jonauskaite, D., Thalmayer, A. G., Müller, L., & Mohr, C. (2021), What does your favourite colour say about your personality? Not much, *Personality Science*.

Kandinsky, W. (2012), *Concerning the spiritual in art*, Courier Corporation.

Lüscher M*.,* (1976)*, Il test dei colori*, Astrolabio.

Malfatti, M., (2014), *Shape-to-color associations in non-synesthetes: Perceptual, emotional, and cognitive aspects*, PhD Dissertation, University of Trento.

O'connor, Z. (2011). Colour psychology and colour therapy: Caveat emptor, *Color Research & Application*, 36(3), pp. 229-234.

Oleari C., (2008), *Misurare il colore, Fisiologia della visione a colori Fotometria-Colorimetria e norme internazionali*, Hoepli.

Valdez, P., & Mehrabian, A. (1994). Effects of color on emotions, *Journal of experimental psychology: General*, 123(4).

Gage J. (1999). *Color and Meaning: Art, Science, and Symbolism*, University of California Press, pp.32.

Historical glazes: Enhancing their value through reproduction and characterisation

Aránzazu Llácer-Peiró[1], Miquel Àngel Herrero-Cortell[2], M. Antonia Zalbidea-Muñoz[3], Laura Fuster-López[1]

[1] *Instituto Universitario de Restauración del Patrimonio*

[2] *Departamento de Comunicación Audiovisual, Documentación e Historia del Arte, UPV*

[3] *Departamento de Conservación y Restauración de Bienes Culturales, UPV*

Corresponding author: Aránzazu Llácer-Peiró (arllapei@cap.upv.es)

ABSTRACT

This text presents a visual study of historical glazes made with lake pigments and dyes, applied on colour gradients used historically between the 15th and 17th centuries. This pictorial reproduction was carried out using materials and methodologies no longer in use, seeking methods of reproduction as close as possible to the pictorial processes used in the 15th and 17th centuries. This made it possible to evaluate the different results offered by the glazes applied to the basic colours from a visual and empirical point of view. For this study, several test pieces were made using nine pigments in the base layers on which different glazes were applied in several superimposed layers. To prepare the glazes, different types of lake pigments and dyes were used, all of them with different concentrations/thicknesses (from one to four coats). They were used to obtain different chromatic nuances that allow us to evaluate material, visual or perceptual aspects, highlighting the extent to which the glazes can alter, shading or accentuating the underlying colour. These data were quantified and assessed by means of homogeneity coefficients, colouring power, hiding power and particle visibility.

KEYWORDS: lake pigments, dyes, transparencies, glazes.

RECEIVED 17/05/2023; **REVISED** 28/06/2023; **ACCEPTED** 18/07/2023

1. Introduction

The concept of glazing has been interpreted throughout history in different ways. In fact, its current meaning is relatively recent and, therefore, the term itself is not found in ancient treatises or recipe books[1] Mentions or allusions are found to the 'act of veiling' in these historical sources, describing techniques that suggest that the application of translucent layers of colour over a more opaque one, in order to alter, shade, change or accentuate the underlying colour, was known and commonly used as early as the 12th century (Gollini, 2020). As they are very thin layers, glazes are usually very fragile and delicate, and due to the organic nature of their materials they are more unstable in the presence of light and humidity, which causes them to degrade and even dissolve (Matteini, 2001). For this reason, as they are often mistaken for repainting or layers of deteriorated varnish, they are frequently removed. The insufficient study of glazes has sometimes led to their complete removal in the restoration and cleaning processes of many artworks. As a result, there are numerous facts that reveal the lack of knowledge about the technical and material aspects of the work linked to glazes, leading to their systematic elimination.

In addition to the well-known texts by Cesare Brandi (Brandi, 1995; Brandi, 1949), it is worth mentioning that of René Huyghe (Hernández, 2019), art historian and curator of the Louvre since 1937, who, in response to the controversy raised regarding the excessively radical restoration criteria of the National Gallery, questioned the cleaning methods proposed by this institution, pointing out that a "total" cleaning of the work may not return it to its original state, but could even remove glazes that played an essential role in the final appearance of the artwork.

Faced with this lack of historical consideration, on the one hand, and on the other, the inherent fragility that characterises both the material and the technique of the glaze, the aim of this article is to investigate this element through experimentation and reproduction with pigments (as a base paint), lake pigments and dyes that formed part of the pictorial palette from the 15th to the 17th century. The aim has been to describe and characterise glazes from a visual point of view, considering factors such as tone, colouring and covering power, homogeneity of the layer and visibility of the particle.

2. Materials and methods

With the aim of investigating the nature and characteristics of the glazes used between the 15th and 17th centuries, this work proposes the study of pictorial superimpositions made with lacquers and dyes, on chromatic bases made with different earth pigments (ochre, raw sienna, raw umber, burnt umber, *Herculaneum* red and green earth), lead white, vine black, azurite and vermilion.

For this purpose, twelve glazes were reproduced using dyes and lacquers, applied on the nine chromatic bases already mentioned, using 35x35 cm slabs prepared with calcium sulphate ($CaSO_4$), calcium carbonate ($CaCO_3$) and rabbit skin glue. Nine squares coloured with pigments agglutinated with linseed oil, progressively reducing their saturation by adding lead white, were applied to each tablet (Figure 1). All the pigments were ground, refined and agglutinated, reconstructing the historical procedures recovered from the sources. The following pigments were used for the nine chromatic bases on which the resulting glazes were applied[2] :French Ochre (40010, Kremer), Lead White (46000, Kremer), Raw Sienna (0263, CTS), Raw Umber (0266, CTS), Burnt Umber (0261, CTS), Herculaneum Red (0316, CTS), Vermilion (42000, Kremer), Vine Black (47000, Kremer), Green Earth (0264, CTS) and Azurite (10200, Kremer).

Fig. 1. Application of the chromatic bases on the boards

The twelve glazes were produced using lacquers and dyes, all supplied by Kremer: carmine naccarat (42100), *lac dye* (36020), madder lake coral (372051), dark red (372141), madder lake violet (37218), reseda (36262), aloe (38010), *stil de grain* (37394), indigo (36002), sap green (37391), *atramentum* (12030) and sepia (12400).
As already noted in previous studies (Bomford, et al., 1995), for the application of these pigments in the form of glazes it was necessary to use a varnish (oleoresin) as a binder and thus guarantee an adequate ratio of absorption and drying between the oil and the colouring matter, thus obtaining the desired visual result. There are many sources that refer to the use of varnishes as binders, particularly for pigments that dry with difficulty. Among some examples, the 16th century *Marciana Manuscript* describes how varnish is an excellent binder both for oil painting and for other painting techniques (Merrifield, 1849b). Also, in the same century Giovanni Battista Armenini, suggests adding "[...] oil and a little common varnish, because this varnish is of such a quality that it gives strength and helps all colours that suffer from drying [...]"[3] (Armenini, 1587).

In this work, a varnish made from linseed oil and mastic resin was used as a binder for the dyes and lake pigments to be applied as glazes. Mastic resin was widely used in the production of paintings from the 9th century to the end of the 19th century. It is a soft triterpenoid resin of natural vegetable origin obtained from the mastic tree *(Pistachia lentiscus. L),* which is abundant on the Mediterranean coasts (Zalbidea Muñoz, 2014). On this occasion, the varnish used consisted of two parts linseed oil to one part resin, thus reproducing the recipe described by Theophilus in the 12th century in his treatise *De diversis artibus* (Theophilus, 1847; Zalbidea Muñoz *et al.,* 2017; Zalbidea Muñoz *et al.*, 2022).

Once the lake pigments and varnish had been bound together, superimposed layers of glazes were applied on top of the base colours, thus generating a gradation in the saturation of shades (Figure 2). When preparing these mixtures, due to the different properties of the lacquer pigments, it was necessary to carry out tests on the proportions of lacquer and varnish needed to apply the glazes, considering their hiding power, ease of application and dissolution of the particle in the medium.

The glazes reproduced in this study are detailed in the next sections.

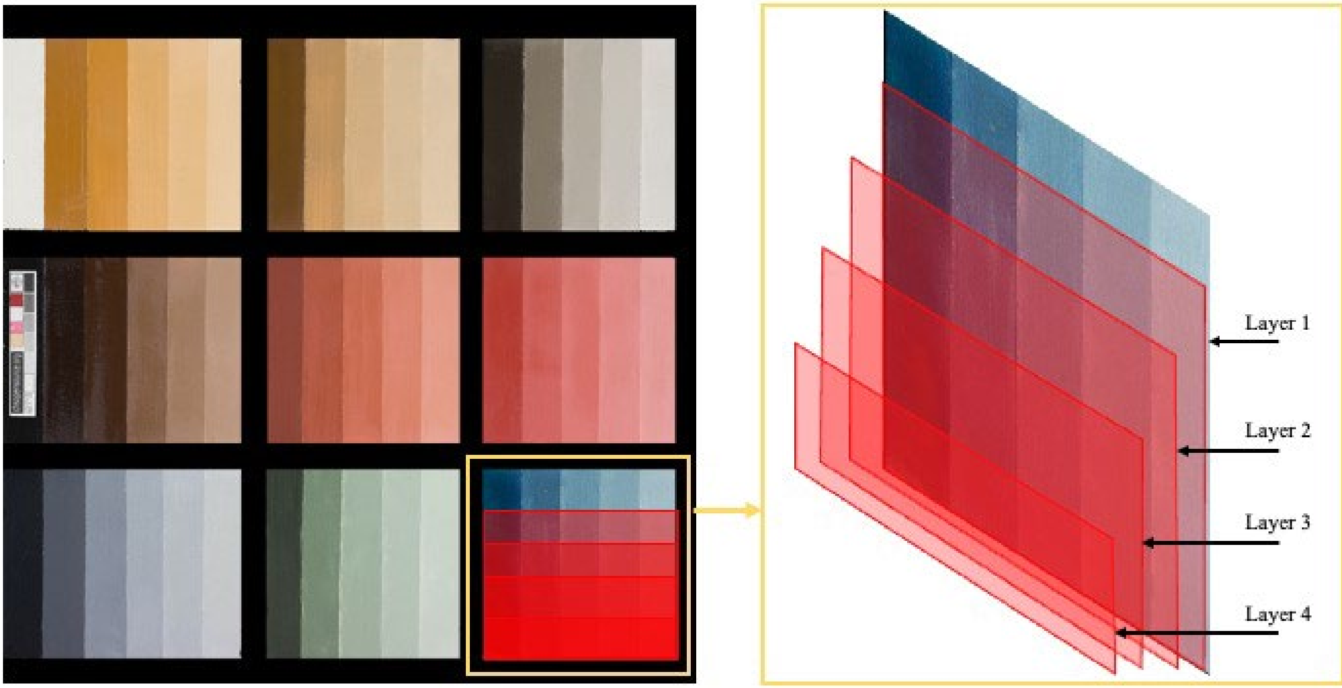


Fig. 2. Graphical representation of the application of layers of glazes. On the left, the table with the nine base pigments and their different degrees of saturation is shown. On the right, the application of the different layers of glaze superimposed on one of the base pigments is shown.

2.1. *Reds*

Historically, lakes (or lake pigments) of red tone were obtained from the madder roots (Rubia tinctorum L.), or from insects such as *Kermes Vermilio* L., known as *Kermes Vermilio Planch* L. (López, 2002), but also from parasites of *Quercus coccifera* L. (Kirby *et al*., 2014) and *Coccus Ilicis* L., which infest respectively the leaves and branches of oaks and holm oaks such as *Quercus ilex* L. (Gettens & Stout, 1966). These reds have been widely used throughout history for their application as glazes in oil painting (Leona, 2009). The use of madder as a dye for fabric dyeing and lakes production has been known since ancient Egypt, Rome and Greece (Mayer, 2005). The proportions of alizarin and other anthraquinone present in the root of the plant determine the shade of dye obtained, as does the different way in which they are processed (even the temperature of the water has an influence), giving rise to shades ranging from red to purple (Hofenk de Graaff, 2004). In this way, three shades have been obtained from the madder that have been applied as glazes: madder lake coral, dark red and madder lake violet. As far as red lacquers of animal origin are concerned, carmine naccarat is obtained from the American variety of cochineal called *Coccus Cacti* L. This variety began to be imported from the Americas in the 16th century, progressively banishing the lac obtained from *Kermes Vermilio* L., a parasite of *Quercus coccifera* L.

(Zalbidea Muñoz & Herrero-Cortell, 2022). As for lac dye, it also originates from the secretion of another insect similar to the cochineal called *Coccus Lacca* L. or *Kerria Lacca* L. Its colour is similar to those obtained from cochineal and kermes, but warmer. As Scott points out, although it is more permanent than cochineal, it is less glossy, and the glaze is denser than that obtained with cochineal (Scott, 1885).

2.2. *Yellows*

Among the most lightfast natural dyes, yellow lakes have been widely used in the textile dye market, where they are also used as a complementary shade to obtain other colours such as orange or green (Herrero-Cortell, 2019). Reseda (also known as *arzica*) has stood out as one of the most widely used yellow dyes throughout the history of art and despite its low colouring power compared to other yellow dyes, it provides a very intense tone (Gettens & Stout, 1966). As in the case of red lakes, the obtaining of reseda lake is subordinated to the addition of essential compounds such as, for example, alum. But also, the addition of small amounts of lead white gives it a higher opacity (Bomford *et al.,* 1995). A second example of yellow dye used in the study is *stil de grain*. Merrifield (1849a) notes that in France this term describes the range of lake pigments from pure yellow to green-tinted yellows. It is a dye derived from the processing of the unripe berries of the *Rhamnus* L*.* plant (Eastaugh *et al*., 2008). Water and soda are used to extract the colouring matter which, when precipitated on clay, was used in ancient times as a yellow lake (Doerner, 2001) and which, according to Watin (1773), can be used as a transparent glaze when alum is added. Another material used to produce yellow lakes is aloe. For its preparation it was not necessary to use mordants. It is known to be used as a supplement in varnishes and glazes (Merrifield, 1849a) or as a pigment for the preparation of glazes (Eastaugh *et al*., 2008) to accentuate or enliven the shades on which it was applied.

2.3. *Blues*

Used since ancient times, indigo has been applied throughout Europe since the 14th century as a complement to azurite and ultramarine (Doerner, 2001). It is not uncommon to find it combined with red lacquers to obtain violet shades and its use to highlight shaded areas is already mentioned in the medieval Strasbourg manuscript (van Eikema Hommes, 2002). Insoluble in water, it is obtained from the plant *Indigofera* L. A second common variety in Asia is pastel blue or glasto, extracted from the leaves of *Isatis tinctoria* L., which is widely used for pictorial purposes in Europe (San Andrés *et al.,* 2010). Indigo together with lead white was applied to reduce the intensity of the blue or was fixed to fillers (lime or white clays) to create pigments with more body (Herrero-Cortell, 2019), and in this way very colourful blue mixtures were obtained, emulating azurite.

2.4. *Greens*

Green lakes have not been a regular part of the pictorial palette, as this tone could be obtained from a mixture of yellows and blues. The fact that green earths bound with oil generate a translucent mixture and that *cardenillo* also has transparent properties determines the low popularity of green lakes in artistic palettes (Herrero-Cortell, 2019). However, de Mayerne (1620) describes this colour as suitable for shading other greens, even when used in several layers. The same author mentions obtaining greens with yellow, *massicot* and cobalt blue lakes (Eastlake, 1847). In this experiment, glazing with sap green has been applied. In the *Manoscritto Bolognese (De Fiendis viridibus),* among other recipes, it is described how to obtain this lake pigment from crushed buckthorn berries, exposed to the sun and with the addition of alum (Merrifield, 1849b).

2.5. *Blacks*

The composition and nature of *atramentum* is not yet defined (Zalbidea Muñoz, 2014). Vitruvius in his *De Architectura* (1st century BC) describes its preparation from the soot produced by the combustion of resin or the embers of resinous wood. Pliny (*Storia Naturale* I century AD) also relates this term to a final varnish or glaze with a protective as well as aesthetic intention (Giannini, 2008). The *atramentum* provided by Kremer Pigmente comes from the tannic acid of oak galls, produced by the bite of an insect that leaves its eggs in the tree stems (generally of the genus *Quercus L.*). In most cases, this ink was used to outline the figures and to darken specific areas (Herrero-Cortell, 2019).

On the other hand, sepia colour is obtained from the ink sacs of some cephalopods. It provides a very dark and semi-transparent colour and is therefore excellent for use in watercolour techniques (Mayer, 2005). It has a great colouring power and is very suitable for working in both aqueous and oily media, although watercolour allows for a multitude of shades and tones (Terry, 1893).

3. Results and discussion

After application of the glazes, the behaviour of each of the lakes and dyes applied was observed. The results obtained according to the above-mentioned criteria are described below:

3.1. *Reds*

As mentioned above, the colour tone of the lakes from madder can vary depending on the mordant used, but also on the proportions of alizarin, purpurin or pseudopurpurin contained in the root from which the colouring matter is extracted (San Andrés *et al.,* 2010; Schweppe & Winter, 1997). Likewise, red lakes of animal origin provide different shades depending on the mordant used or the insect of origin. The translucent property of carmine naccarat (Figure 3) makes it suitable for use as a glaze (Schweppe & Roosen-Runge, 1997). This characteristic is observed in the test tube made with this lake, giving a very intense magenta colour. Lac dye and madder lake violet have a high colouring power from the first coat of application (Figures 3 and 4), with the dark red glaze generating the least saturation and colour intensity (Figure 4). The coats applied with carmine naccarat, lac dye and madder lake coral were more homogeneous, with madder lake violet being the glaze that generates very visible particles (Figure 4 and 5). Most of these lakes had a high/medium hiding power which, in some cases (carmine naccarat and lac dye), almost hid the underlying base pigment in the fourth glaze layer.

Fig. 3. Glazes made with carmine naccarat (1) and Lac Dye (2)*

Fig. 4. Glazes made with madder lake coral (1), dark red (2) and madder lake violet

3.2. *Yellows*

The yellow lakes have little covering and colouring power, although in the case of *stil de grain*, the superimposed layers of glaze generate changes in the underlying tonality. In all cases except for the reseda, the dye particles are visible, forming an inhomogeneous layer (Figures 5 and 6). As for aloe, at least three coats of polish are needed to create changes in the underlying shade.

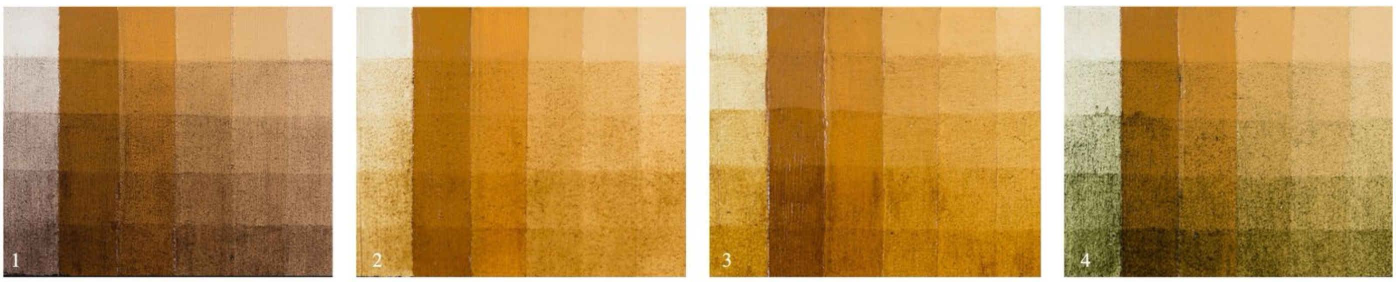


Fig. 5. Details of particle visibility in applied glazes with madder lake violet (1), aloe (2), stil de grain (3) and sap green (4)

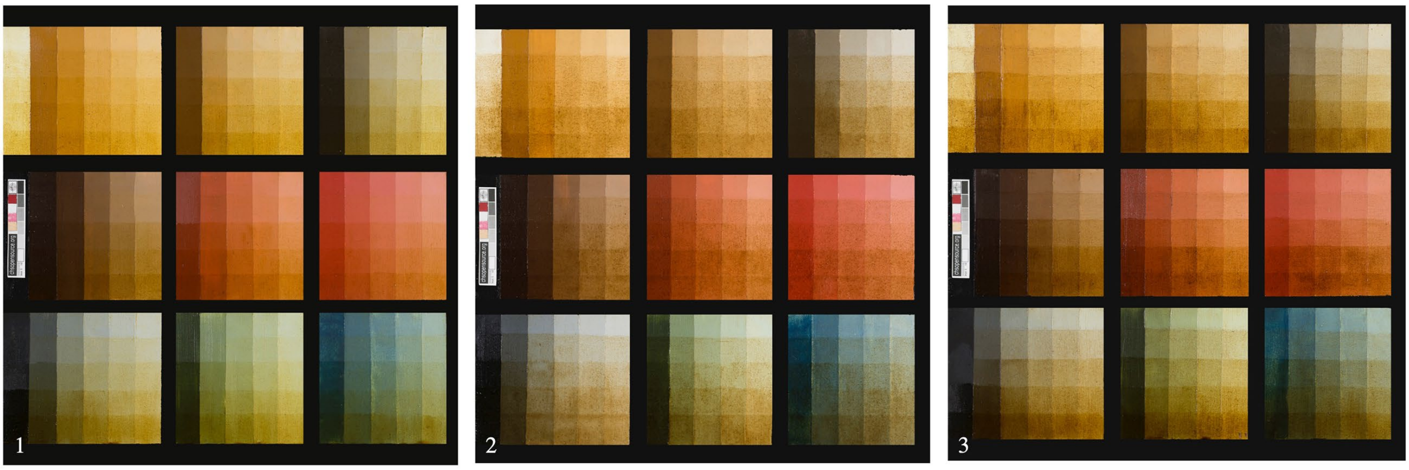


Fig. 6. Glazes made with reseda (1), aloe (2) y stil de grain

3.3. *Blues*

As shown in Figure 6, indigo has an unattractive shade, although as Ball (2012) notes, it becomes more pleasing when mixed with white. The dye particles are moderately visible. It has a high colouring and hiding power and produces homogeneous and uniform glazes. This quality was optimal for creating shadows on fabric folds (Artoni *et al*., 2019).

3.4. *Greens*

The glaze applied with sap green (Figure 7) has a dark green tone, with little colouring and hiding power and in which the presence of particles of the dye is evident (Figure 5). The layer is not very homogeneous in its application, so it is very likely that it was not used in extensive glazes. Therefore, it was very common to apply glazes with copper resinate based on a mixture of *verdigris* with resin, as a more homogeneous and saturated result was obtained than with sap green (Doerner 2001).

3.5. *Blacks*

Atramentum has a brown colour, very similar to madder lake violet, but unlike the latter, it behaves very uniformly in all applications and has a high hiding power (Figure 7). It can be seen how this glaze on the vine black creates a chromatism similar to that produced by the base pigment. Also characterised by a very homogeneous and uniform film in which the dye particles are barely perceptible, sepia provides a brown shade similar to *atramentum* although it shows more opacity, high hiding power and colouring (Figure 7).

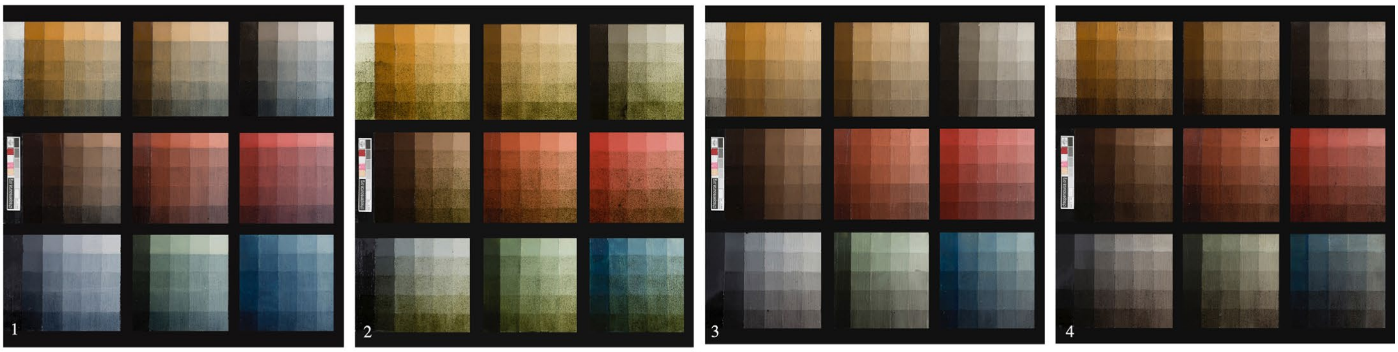


Fig. 7. Glazes made with indigo (1), sap green (2), atramentum (3) and sepia (4)

4. Conclusions

After application of the glazes on all the test pieces, relevant conclusions were drawn. As the literary sources show, the range of red dyes generates multiple shades. The origin of these lakes (vegetable or animal), as well as the mordant used for their production, leads to shades ranging from deep red to dark brown. The red glazes applied with carmine naccarat, lac dye and madder lake coral have generated a uniform layer, creating very covering films with high colouring power. As for the yellow tones applied with reseda, homogeneous glazes have been created, but with low covering and colouring power. Even so, authors such as Herrero-Cortell (2019) recall that this lake has been widely used to achieve other complementary colours. Both *stil de grain* and aloe have created more saturated layers of colour in successive applications, but the dye particles are quickly visually perceptible. In the range of blue shades made with indigo, very homogeneous glazes with high covering power were created, thus confirming the words of Artoni (2019) who stated that its properties were optimal for providing depth and shadows on fabrics. As Ball stated, it was also observed that indigo glazes applied on white tones generate softer shades (Ball, 2012). In this test tube, the dye particles are also visible to the naked eye, although in other experiments they may not be visible, due to the milling process used (Figure 7).

The sap green has a dark shade. As can be seen in the test tubes, this lake does not offer homogeneous results, being difficult to handle and bind by hand. As pointed out by several authors (Herrero-Cortell, 2019; Mayerne, 1620; Eastlake, 1847), the existence of other formulas for obtaining the green colour means that this lake has not been popular for application as glazes. Given its lack of homogeneity, it is very likely that it was not used for large or extensive glazes, but only in limited or localised areas.

As for black tones, both *atramentum* and sepia, usually applied to accentuate shadows, have generated very homogeneous glazes of high chromatic intensity.

5. Conflict of interest declaration

The authors wish to state that no financial or personal interests have affected the objectivity of the study, and that no conflicts of interest exist.

6. Funding source declaration

This research has been carried out within the framework of the PID 2019-106616ES-100 project awarded by MCIN/ AEI /10.13039/501100011033.

7. Short biography of the author(s)

Laura Fuster-López - Professor at the Conservation Department in the Universitat Politècnica de València (Spain). After several research fellowships at Europe and the United States, she got her PhD in Conservation from UPV where she coordinates the area on the study of the mechanical and dimensional properties of cultural materials since 2007. She has been involved in numerous international R+D projects always with a special focus on understanding the mechanisms involved in paintings behavior and degradation.

Mª Antonia Zalbidea-Muñoz - Professor in the Department of Conservation and Restoration of Cultural Heritage at the UPV, field in which she holds a doctorate degree. She has directed her research on the procedural, material and conservative aspects of mural painting, as well as parts related to varnishes and dyes in painting. At present she is also a collaborator in the work team of the project: Byzantine illuminated manuscripts in Spain: work, context and materiality - MABILUS (MICINN-PID2020-120067GB-I00).

Miquel Àngel Herrero-Cortell - He holds a PhD in Art History. He has a degree in Fine Arts from the Polytechnic University of Valencia (UPV) and a degree in Art History from the University of Valencia (UV). He holds a Master's Degree in Conservation and Restoration of Cultural Heritage and a Master's Degree in Artistic Production. He has developed his work as a researcher focusing on the field of materials and painting techniques, as well as on painting diagnosis. He is currently teaching at the Universitat Politécnica de València.

Aránzazu Llácer-Peiró - Research Technician pursuing the PhD in Conservation at Instituto Universitario de Restauración del Patrimonio (Universitat Politècnica de València) on the study of drying pigments through a multi-analytical approach.

Notes

[1] In the Middle Ages, the monk Theophilus in his treatise *De diversis artibus* refers to glazes, without including the term, but alluding to "translucent" paintings (Theophilus, 1847). Also, in his *Treatise on Painting*, Leonardo Da Vinci talks about transparent colors (De Vinci and Alberti). But Giovanni Battista Armenini (1587) is the first author to use the term glazing in his book *De veri precetti della pittura* (Armenini 1820).

[2] For more information, please consult the websites of the pigment suppliers: https://www.kremer-pigmente.com/ and https://shop-espana.ctseurope.com/

[3] The original text saids: "...añadiendole aceite y un poco de barniz común, porque este barniz es de tal calidad que da fuerza y ayuda a todos los colores que sufren al secarse…" (Armenini, 1587).

Licensing terms

References

Armenini, G. B. (1587). *De los verdaderos preceptos de la pintura* (2000th ed.). Visor Libros.

Artoni, P., Raïch, M., Herrero-Cortell, M., & Ricci, M. L. (2019). Riconoscere dal colore. Pigmenti e coloranti dell'età moderna nell'analisi multibanda dei dipinti: Uno strumento visivo per gli storici dell'arte e i conservatori. *Colore e Colorimetria. Contributi Multidisciplinari. Atti Della Quindicesima Conferenza Del Colore, a Cura Di A. Bottoli e V. Marchiafava.*

Ball, P. (2012). *La invención del Color*. Madrid: Turner.

Bomford, D., Dunkerton, J., Gordon, D., & Roy, A. (1995). *La pintura italiana hasta el 1400. Materiales, métodos y procedimientos del arte*. Barcelona: Ediciones del Serbal.

Brandi, C. (1949) The Cleaning of Pictures in Relation to Patina, Varnish and Glazes, The Burlington Magazine, *(91)*183-88

Brandi, C. (1995). *Teoría de la restauración* (1995th ed.) Madrid: Alianza Editorial.

Cardon, D. (2007). *Natural Dyes: Sources, Tradition, Technology and Science*. London: Archetype Pub.

Doerner, M. (2001). *Los materiales de pintura y su empleo en el arte*. Barcelona: Reverté.

Eastaugh, N., Walsh, V., Chaplin, T., & Siddall, R. (2008). *Pigment Compendium. A dictionary and Optical Microscopy of Historical Pigments*. Oxford: Elsevier Science & Technology.

Eastlake, C. (1847). *Materials for a History of Oil Painting*. London: Longman, Brown, Green - Longmans.

Gettens, R. J., & Stout, G. L. (1966). *Painting Materials. A Short Encyclopaedia*. New York: Dover Pub.

Giannini, C. (2008). *Diccionario de restauración y diagnóstico*. San Sebastián: Nerea.

Gollini, G. (2020). *Potenzialità della tecnica di imaging iperspettrale per lo studio di pitture a olio in presenza di velature*. Tesi di Laurea. Università Degli Studi Firenze.

Hernández, A. (2019). *Documentos para la Historia de la Restauración*. Zaragoza: Prensas Universidad de Zaragoza.

Herrero-Cortell, M. (2019). *Materiales, soportes y procedimientos utilizados en los obradores pictóricos de la Corona de Aragón (siglos XV y XVI). Una aproximación a través del paradigma valenciano*. Tesis Doctoral. Universitat de Lleida.

Herrero-Cortell, M. y Zalbidea Muñoz, M. A., (2022). *Ad faciendum lacham. Notas sobre la producción carmines y lacas rojas en la pintura valenciana de los siglos XV y XVI. 1st European Symposium on Drugs & Colors in History.* Tirant Lo Blanch. *In press.*

Hofenk de Graaff, J. H. (2004). *The colourful past: Origins, chemistry and identification of natural dyestuffs.* London: Archetype Publ.

Kirby, J., Van Bommel, M., & VERHECKEN, A. (2014). *Natural Colorants for Dyeing and Lake Pigments*. Archetype Publications Ltd. https://archetype.co.uk/our-titles/natural-colorants-for-dyeing-and-lake-pigments/?id=209

Leona, M. (2009). Microanalysis of organic pigments and glazes in polychrome works of art by surface-enhanced resonance Raman scattering. *Proceedings of National Academy of Sciences*, *106*(35), 14757-14762.

Llácer, A. (2021). *Veladuras históricas con pigmentos laca: Aproximación teórico-práctica y caracterización en diversas bandas del espectro*. Tesis Final de Máster. Universitat Politècnica de València. https://riunet.upv.es/handle/10251/173723

Llácer, A. y Zalbidea Muñoz, M. A. (2022). *Veladuras medievales con colorantes y pigmentos-laca. De las fuentes a las reconstrucciones experimentales*, Comunicazione Convegno Internazionale *The Traces of the Colorful Souls. Visual and Material Arts in the Chromatic Middle Ages*. Madrid, 2-4 march 2022. Universidad Complutense de Madrid.

López, G. (2002). *Guía de los árboles y arbustos de la Península Ibérica y Baleares: (Especies silvestres y las cultivadas más comunes)*. Madrid: Mundi Prensa Libros.

Matteini, M. (2001*). La química en la restauración: Los materiales del arte pictórico*. San Sebastián: Nerea.

Mayer, R. (2005). *Materiales y técnicas del arte*. Madrid: Tursen - H. Blume

Mayerne De, T. (1620). *Le manuscrit de Turquet de Mayerne* (1967th ed.). Lyon: Audin Imprimeurs.

Merrifield, M. P. (1849a). *Original treatises of the arts of painting:* Vol. I. London: J. Murray, Albemarle St.

Merrifield, M P. (1849b). *Original treatises of the arts of painting:* Vol. II. London: J. Murray, Albemarle St.

San Andrés, M., Sancho, N., y de la Roja, J. M. (2010). Alquimia: Pigmentos y colorantes históricos. *Anales de la Real Sociedad Española de Química*, 1, 58-65.

Schweppe, H., & Roosen-Runge, H. (1997). Carmine-Cochineal Carmine and Kermes Carmine. In Feller. R. *Artists' Pigments. A handbook of their history and characteristics* (Vol. I). London: Archetype Publications.

Schweppe, H., & Winter, J. (1997). "Madder and Alizarin". In Feller. R. *Artists' Pigments. A handbook of their history and characteristics* (Vol. 3). London: Archetype Publications.

Scott, J. (1885). *Field's chromatography: A treatise on colours and pigments for the use of artists*. London: Windsor and Newton. http://archive.org/details/Fieldquotschrom00Fiel

Terry, G. (1893). *Pigments, Paint and Painting: A practical book for practical men*. London: E. & F.N. Spon; New York: Spon & Chamberlain. https://www.gutenberg.org/ebooks/56344

Theophilus. (1847). *Diversarum artium schedula*. London: J. Murray.

van Eikema Hommes, M. H. (2002). *Discoloration in Renaissance and Baroque Oil Paintings. Instructions for Painters, theoretical Concepts, and Scientific Data*. Tesis Doctoral. University of Amsterdam. https://dare.uva.nl/search?identifier=6a808727-7edd-47a7-a561-1e961466f7ff

Watin. (1773). *L'Art du Peintre, Doreur, Vernisseur* (1785th ed.). Paris: Chez L'auteur.

Zalbidea Muñoz, M. A. (2014). *Els vernissos artístics: Revisió i evolució.* València. Universitat Politènica de València. http://hdl.handle.net/10251/66792

Zalbidea Muñoz, M.A., E. Giner-Cordero, "Pratica di tecniche artistiche storiche. Le vernici di Teofilo", KERMES Art Conservation Restoration, 30, (106), 2017, 76-77. https://riunet.upv.es/handle/10251/112366

Zalbidea Muñoz, M. A., Zelazowski, J., y Herrero-Cortell, M. (2022). De diversus artibus, un recetario de tecnología artística para el estudio de los barnices medievales. *1st European Symposium on Drugs & Colors in History.* Tirant Lo Blanch. *In press*

A technique to ensure correct color stimulation by functional MRI to study in vivo the human melanopsin ganglion cells system

Andrea Siniscalco[1], Caterina Tonon[2,3], Micaela Mitolo[3,4], Claudia Testa[5], Marco Gaiani[6], Maurizio Rossi[1]

[1]*Department of Design, Politecnico di Milano, Italy, andrea.siniscalco@polimi.it, maurizio.rossi@polimi.it,*

[2]*Department of Biomedical and Neuromotor Sciences, University of Bologna, Bologna, Italy, caterina.tonon@unibo.it,*

[3]*Functional and Molecular Neuroimaging Unit, IRCCS Institute of Neurological Sciences of Bologna, Bologna, Italy*

[4]*Department of Medicine and Surgery, University of Parma, Parma, Italy, micaela.mitolo@unipr.it*

[5]*Department of Physics and Astronomy, University of Bologna, Bologna, Italy, claudia.testa@unibo.it*

[6]*Department of Architecture, Alma Mater Studiorum - Università di Bologna, Italy, marco.gaiani@unibo.it.*

Corresponding author: Andrea Siniscalco (andrea.siniscalco@polimi.it)

ABSTRACT

This paper describes a methodology to achieve correct light radiation coloring for stimulating intrinsically photosensitive melanopsin retinal ganglion cells. Indeed, it has been shown that light is capable of causing a response from the master circadian pacemaker located in the suprachiasmatic nucleus of the hypothalamus. A study was conducted in an experimental set-up using a high field clinic Magnetic Resonance scanner equipped with a stereoscopic viewer capable of projecting specific wavelengths to stimulate melanopsin retinal system. Subjects were monitored by acquiring Functional Magnetic Resonance Imaging, observing the response in subcortical (i.e., hypothalamus) and limbic areas (i.e., amygdala) and in some cortical areas primarily related to alertness. The spectral radiation emitted by the viewer was measured with laboratory instruments, and some considerations were also made on its possible influence at the level of the circadian cycle.

KEYWORDS Brain, Light treatment, Color stimulation, Functional Magnetic Resonance Imaging, Spectral measurements, Circadian rhythms

RECEIVED 24/06/2022; **REVISED** 07/07/2023; **ACCEPTED** 26/07/2023

1. Introduction

Melanopsin (Opn4) containing retinal ganglion cells (mRGCs) in humans are a subset - about 0.5-1% - of RCG, the output neurons whose axons form the optic nerves (Hattar *et al.*, 2002) and represent the third class of photoreceptor discovered in 2000 (Provencio *et al.*, 2000). The mRGCs act as an intrinsically photosensitive system contributing to image and mainly non-image-forming (NIF) visual circuits (Hattar *et al.*, 2002).

The broad spectrum of mRGCs functions includes the synchronization of the biological clock with the light-dark cycle (circadian rhythm photoentrainment), mediated by their projections to the master circadian pacemaker of the mammalian brain, located in the suprachiasmatic nucleus (SCN) of the hypothalamus, and the pupillary light reflex through the projection to the olivary pretectal nucleus (OPN) (La Morgia, Carelli and Carbonelli, 2018). More recently, several studies have pointed to the role of mRGCs in regulating the effect of light in several behavioral and physiological functions such as sleep, cognitive functions- learning or memory - and mood (LeGates, Fernandez and Hattar, 2014).

The functional integrity of the circadian regulatory network, partially dependent on melanopsin cells integrity, is crucial for well-being and health (Mure, 2021). Its dysregulation may contribute to sleep, neurodegenerative, and seasonal affective disorders (Mure, 2021). The alteration of the circadian rhythm can occur late, called owl disorder, or early, called lark disorder (Phillips, 2009). Throughout an individual's life, it is pretty common for him/her to be more owlish when young, highly active in the evening but with late morning awakenings, while in old age, they become larks, with fatigue just after sunset and early morning awakenings. The dysregulation of the circadian cycle can cause migraine (van Oosterhout *et al.*, 2018), headaches (Pringsheim, 2002), irritability (Evans and Davidson, 2013), seasonal depression (Rosenthal, 2006), immune system deficiencies (Christoffersson *et al.*, 2014), chronic fatigue (Bonsall and Harrington, 2013), obesity and diabetes mellitus (Cedernaes, Schiöth and Benedict, 2015). It has also been hypothesized that there is an increased likelihood of developing certain cancers as a result of the alteration of the circadian cycle that affects the production of various hormones and the efficiency of the immune system (Stevens and Rea, 2001; Schernhammer *et al.*, 2013; Yadav, Verma and Singh, 2017; Malik *et al.*, 2022).

Studies conducted in vitro and animal models have demonstrated that the spectral sensitivity of the mRGCs ranges from 446 to 483 nm, corresponding to "blue light" (Mure, 2021).

2. Functional Magnetic Resonance Imaging to investigate the response of mRGCs

To address *in vivo* the role of melanopsin expressed by retinal ganglion cells in humans, isolating visual and NIF functions in humans is challenging.

The specific pattern of activation/deactivation in brain regions involved in cognitive functions has been demonstrated in healthy subjects by using different paradigms of monochromatic light stimulation administrated by ad hoc devices integrated into functional magnetic resonance imaging technology (Vandewalle *et al.*, 2007).

Functional Magnetic Resonance Imaging (fMRI) is an advanced in-vivo metabolic MRI technique able to achieve unique insight into brain activity and network connectivity. Introduced at the beginning of the nineties, fMRI (Bandettini *et al.*, 1992; Kwong *et al.*, 1992; Ogawa *et al.*, 1992; Kwong, 2012) can give an indirect measure of brain activity during the administration of specific stimuli without the injection of any intravenous contrast agent. This technique is used in clinical practice for the presurgical planning of lesions in eloquent regions (Castellano *et al.*, 2017) and the field of cognitive neuroscience. Vandewalle and colleagues (2009) reviewed PET and functional MR studies demonstrating that the experimental setting of light exposure - primarily its wavelength, intensity, and duration - modulate brain responses to cognitive tasks administrated via auditory (not visual) system.

Specifically, these responses were observed in subcortical (i.e., hypothalamus) and limbic areas (i.e., amygdala), as well as in some cortical areas mostly related to alertness (i.e., frontal regions) (Vandewalle, Maquet and Dijk, 2009). Moreover, Evangelisti and colleagues (2020) also explored in Leber's Hereditary Optic Neuropathy (LHON) the mRGCs' contribution to light-driven visual and cognitive brain responses. In these disorders, optic nerve atrophy occurs consequent to retinal ganglion cells (RGCs) degeneration in the inner retina, while mRGCs are relatively spared. Authors found higher occipital activation in response to blue vs. red stimulation and larger brain responses over the lateral prefrontal cortex in LHON under blue vs. red light (Evangelisti *et al.*, 2021).

Most recently, other studies demonstrated age-related loss of optic nerve axons and specifically mRGC loss in postmortem Alzheimer's Disease (AD) patients associated with Aβ deposition. These results support the concept that mRGCs degeneration contributes to circadian rhythm dysfunction in Alzheimer's Disease (AD) (La Morgia *et al.*, 2016; Ortuño-Lizarán *et al.*, 2018);

however, other studies with specific fMRI protocols are strongly needed to confirm this evidence in vivo. Considering the key role of mRGCs on circadian rhythms and sleep, this system of intrinsically photosensitive mRGCs represents a potential target for therapeutic exploitation using bright light. Although the absence of randomized controlled trials in this field, a recent systematic review demonstrated that Bright Light Treatment (BLT) is a promising intervention in patients affected by dementia, specifically in Alzheimer's Disease (AD), and does not have significant adverse effects (Mitolo *et al.*, 2018).

3. Instrumentation Specifications

In the setup of the present study, light is safely conveyed via a purpose-built 3D-printed stereoscopic visor.

The visualization device consists of a binocular head-mounted display (HMD) (NordicNeuroLab) featuring a 28.6° horizontal x 20.3° vertical field of view. This device is designed to provide high-resolution images to the subject lying down on the MRI scanner bed (thanks to the material used and the length of the cable), both for patient comfort and for visual task-based functional imaging applications.

Fig. 1. The MR system compatible stereoscopic visor has two OLED displays and integrated eye-tracking cameras to both real-time visual monitor and record direction of gaze and pupil diameter.

Displays consist of dual SVGA active-matrix OLED microdisplays produced by eMagin (*eMagin*, 2023) and presenting a resolution of 800x600 pixels @85Hz. The displays viewing area is 12.78 x 9 mm, the contrast ratio ≥300:1, uniformity is > 85%, and White Luminance Maximum (Color) ≥ 140 cd/m^2 (front luminance) for SVGA 60Hz VESA mode. The sRGB color space is fully covered.

Symbol	Parameter	Min	Typ.	Max.
CIE White	X	0,270	0,320	0,370
	Y	0,290	0,340	0,380
CIE Red	X	0,565	0,574	-
	Y	0,338	0,347	0,360
CIE Green	X	0,240	0,300	0,340
	Y	0,450	0,500	-
CIE Blue	X	0	0,168	0,200
	Y	0	0,158	0,200

Tab. 1. CIE white point and primaries coordinates.

The visual stimulus is enabled using images coded as TIFF file format, 24-bit RGB color in the Apple Display P3 color space. As a result, it minimizes most of the downsides of the sRGB color space, the most used today.

x_R	y_R	x_G	y_G	x_B	y_B
0,680	0,320	0,265	0,690	0,150	0,060

Tab. 2. Coordinates of the primary used.

The Display P3 color space is 26% larger than the tiny sRGB color space, and it can accurately reproduce vivid colors, such as yellow cadmium and, mainly in our case, blue cobalt, clipped in the sRGB color space. It can be viewed almost entirely on most medium-high-end smartphones and totally on professional monitors such as the Apple XDR. This color space is a variant of the DCI-P3 color space using the D65 illuminant instead of the D50 and a gamma of 2.2, as in the sRGB color space.

These changes allow a more consistent workflow and visualization for devices supporting only the sRGB color space colors because the area of the sRGB color space is fully covered by the Display P3 color space.

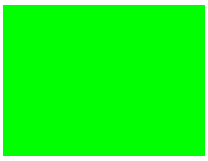
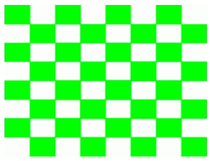
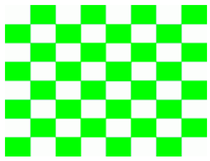
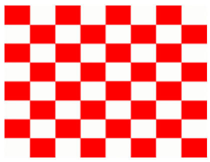
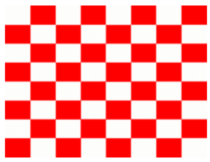
The hardware image pipeline is consistent with this choice. First, a PC enables it with a graphic card Nvidia GeForce RTX 2060, a performance-segment graphics card launched in 2019 that guarantees resolutions of up to 4K 12-bit HDR at 144Hz on two monitors. Then the signal is handled on a Brain Product Trigger Box to be sent to the displays via a 6 meters long optical fiber cable exploiting a 16-bit connection.

4. Spectral measurements

Spectral measurements to evaluate the visible radiation emitted by the visor have been done to get feedback on the radiation that will reach the patient's visual system.

Sample images were chosen for the measurement and projected into the eyepieces of the visor.

The eyepiece was immobilized on a plane, and the measurements were conducted by eliminating the presence of stray light by covering the entire setup with blackout sheets.

		
Ch_blue_all	**Ch1_blue (left)**	**Ch2_blue (right)**
		
Ch_green_all	**Ch1_green (left)**	**Ch2_green (right)**
		
Ch_red_all	**Ch1_red (left)**	**Ch2_red (right)**

Tab. 3. Images were projected in the binoculars during the measurements. The full-colored samples (Ch_blue_all, Ch_green_all to Ch_red_all) were measured in both the eyepieces, while the remaining ones (the chessboards) left and right were both measured, but results are separated due to the different patterns.

The spectral data measured on each sample are:

- Tristimulus values from CIE1931 (X, Y, and Z).
- CIE 1931 color coordinates (x, y).
- CIE UCS 1960 color coordinates (u, v).
- CIE UCS 1976 color coordinates (u', v').
- Spectral radiance in the range 380 - 780 nm, with a step of two nanometers from which the total radiance value is obtained.

The instrument used is a PotoResearch SpectraScan PR701s with a standard MS55 objective, making it possible to measure the spectral radiance at a solid angle with an aperture of 0.5°. The measurements were made after the instrument's 10' heating period to favor its thermal stabilization. The ambient temperature was about 25°C.

Wavelength range	380-780 nm
Aperture	1/2°
Luminance accuracy	±2% referred to NIST with standard illuminant at 2856 K
Luminance precision	The standard deviation of repeated measurements over a 30' period is less than 0.1% when the instrument is operating under normal operating conditions
Colorimetric accuracy for standard illu-minant CIE A	CIE 1931 x±,0015 y±,001
Color precision	±,005 for CIE 1931 x, y by measuring the standard illuminant CIE A
Polarization error	>=5% when measuring 100% linearly polarized sources
Digital resolution	65535:1 (16 bits)
Integration time	From 25 ms to 60000 ms

Tab. 4. Technical characteristics of the SpectraScan PR 701s spectroradiometer.

4.1. *Spectral measurement results*

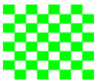
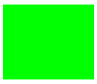
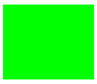
The colorimetric values detected are shown in table 5, while the graphs shown in figure 2 have been created from the spectral radiance values for the wavelengths considered. In abscissa, the wavelengths are reported, while in ordinate, it is possible to observe the radiance values expressed in W/sr/m^2.

4.2. *Evaluations on the circadian response*

In addition to the in vivo observations on the brain's reaction to light stimulation, with the measured spectral radiance values, it is possible to consider the possibility that the light produced by the visor may influence the circadian cycle.

It is now known that the factors regulating the circadian system are very different from that of the human visual system (Rossi, 2019). In the retina-hypothalamus tract, numerous non-image-forming channels interact with the biological clock in the supra-chiasmatic nucleus (SCN) of the hypothalamus in the brain. The normal circadian cycle is generated by the SCN and is synchronized thanks to the succession of local light/dark cycles. These cycles are essential for the sustenance of life. Their aberrant behavior can lead to numerous problems, such as obesity, fatigue (Reiter *et al.*, 2012), and breast cancer (Davis, Mirick and Stevens, 2001).

As expected, however, the human spectral sensitivity for the circadian system is significantly different from that of the visual system. For example, the visual system refers to a Gaussian-like sensitivity curve commonly known as Vλ, which peaks at 555 nm, while the spectral sensitivity curve relative to the circadian system (Cλ) appears to peak, according to many of the studies conducted, a value of 460 nm.

Sample												
Name ocular	Ch1_blue (left)	Ch1_green left)	Ch1_red (left)	Ch_blue_all (left)	Ch_green_all (left)	Ch_red_all (left)	Ch_red_all (right)	Ch_green_all (right)	Ch_blue_all (right)	Ch2_blue (right)	Ch2_green (right)	Ch2_red (right)
X	16,690	21,000	22,200	4,236	12,130	13,760	14,770	13,360	4,338	16,940	21,190	22,490
Y	18,500	26,940	20,290	4,498	19,490	8,625	9,001	22,130	4,597	18,900	27,570	21,410
Z	18,080	14,570	10,970	11,670	7,432	1,763	1,557	8,365	13,120	18,180	15,190	11,930
x	0,3134	0,3360	0,4153	0,2076	0,3107	0,5698	0,5831	0,3045	0,1967	0,3136	0,3313	0,4028
y	0,3473	0,4310	0,3795	0,2205	0,4990	0,3572	0,3555	0,5047	0,2085	0,3499	0,4311	0,3835
u	0,1917	0,1792	0,2471	0,1588	0,1485	0,3708	0,3824	0,1442	0,1541	0,1908	0,1765	0,2370
v	0,3186	0,3448	0,3387	0,2529	0,3579	0,3487	0,3497	0,3585	0,2449	0,3195	0,3444	0,3386
u'	0,1917	0,1792	0,2471	0,1588	0,1485	0,3708	0,3824	0,1442	0,1541	0,1908	0,1765	0,2370
v'	0,4779	0,5172	0,5080	0,3793	0,5368	0,5230	0,5245	0,5377	0,3673	0,4792	0,5166	0,5079
Total radiance [W/sr/m²]	0,06553	0,07774	0,06681	0,02424	0,04863	0,03087	0,03235	0,05487	0,02604	0,06609	0,07954	0,06957

Tab. 5. The table shows the colorimetric coordinates for all the measured samples (columns). The first three rows of the data are the tristimulus values from CIE1931 (X, Y, and Z), following the CIE 1931 color coordinates (x, y), the CIE UCS 1960 color coordinates (u, v), the CIE UCS color coordinates 1976 (u', v') and the total radiance (W/sr/m²).

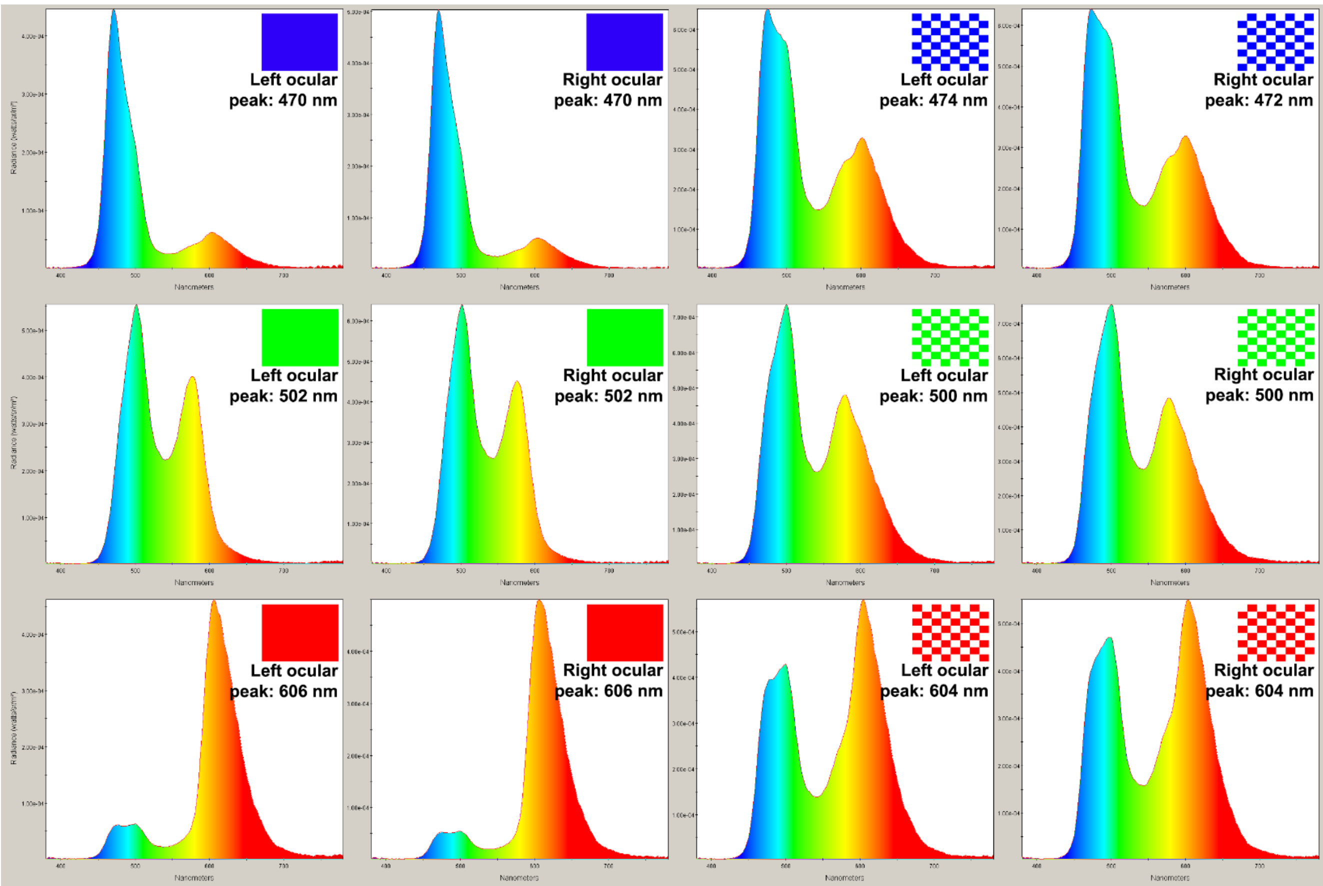


Fig. 2. Cartesian diagrams of the spectral radiances measured for the samples.

 DOI: 10.23738/CCSJ.150206

The exposure of the visual system to radiation around this wavelength cane reduce the production of melatonin (a hormone linked to the propensity to fall asleep) by the pineal gland.

Over the last twenty years, numerous studies have been conducted that have led to the construction of some models of spectral sensitivity for the human circadian system.

The first two research (Brainard *et al.*, 2001; Thapan, Arendt and Skene, 2001), conducted empirically, paved the way for subsequent studies and numerous discoveries that underline that the regulation of circadian cycles by light is not linear and straightforward.

The photo-transduction of the light into a signal transmitted to the SCN has as central actors the mRGCs, which perform their function thanks to their primary photo-pigment, melanopsin, whose functioning and absorption spectrum (maximum sensitivity at 460 nm) are well known.

Despite the identification of this mechanism, however, it has been demonstrated (Rea, Bullough and Figueiro, 2002) that it is not sufficient to evaluate the spectral sensitivity of a single opsin to predict the circadian response of the system. Indeed, mRGCs are not the only actors in the phototransduction phenomenon. They receive information from other photo-pigments (Hattar *et al.*, 2002) and from rods and cones photoreceptors (Belenky *et al.*, 2003).

This is also observable from the discontinuity between 470 and 530 nm of the empirical models of Brainard et al. and Thapan et al. Despite these observations, however, a specific model (Gall, 2004), which ignores these discontinuities, has established its reliability and is still widely considered in the design practices of lighting products that follow the principles of *human-centric lighting*.

For the evaluation of a possible circadian response induced by the stereoscopic visor, the non-linear model proposed by Rea et al. was used (Rea *et al.*, 2012; Figueiro and Rea, 2013), which considers numerous factors, including the transmission of light through the lens of the crystalline lens and the spectral opposition of the blue and yellow channels (Dacey and Packer, 2003).

This non-linear mathematical model results in a quantity called *Circadian Light* (CL_A), which is thought to be normalized so that 1000 CL_A corresponds to 1000 lux emitted by the CIE standard illuminant A (CIE, 1986). This expedient allows to consider light from the point of view of its interaction with NIF channels and applies to all possible spectral radiations. The CL_A value is therefore related to a quantity called *Circadian Stimulus* (CS), which represents the efficacy of CL_A in causing a significant circadian response in terms of inhibition of nocturnal melatonin (Rea *et al.*, 2010).

4.3. *Illuminance measures*

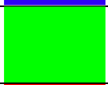
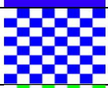
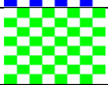
In order to assess whether the visor is capable of provoking a circadian response in terms of CL_A and CS, it was necessary to carry out additional measurements. For the calculation, it is required to have the photopic vertical illuminance value at the height of the cornea produced by the various samples evaluated in the spectral measurements.

Using the same viewer and the same measurement conditions, the vertical illuminance values were measured for each sample shown in table 3.

The instrument used was a Dr. Meter® LX1330B illuminance meter at a measurement distance of 0.5 cm from the viewer lens, and the entire setup was covered with blackout sheets to avoid stray light. The ambient temperature was about 25°C.

Fig. 3. Setup for the illuminance measurements.

The illuminance data and the respective spectral radiance values in the 380-780 nm range, with a step of two nanometers, were entered into two software to calculate CL_A and CS. The tools used were the online spreadsheet *CS Calculator* from Rensselaer Polytechnical Institute in Troy, NY (Rensselaer Polytechnical Institute, 2020) and Osram *Sylvania's LED ColorCalculator* software (OSRAM Sylvania, Inc., 2019). The results are reported in table 6.

Sample	Name (ocular)	Illuminance (lx)	CL_A	CS	Required illuminance (lx) for CS = 0,05
	**Ch1_blue (left)**	1,1	1,8	0,0021	21
	**Ch1_green (left)**	1,3	2,6	0,0031	17
	**Ch1_red (left)**	1,3	2,3	0,0026	20
	**Ch_blue_all (left)**	0,9	4,4	0,0054	6,5
	**Ch_green_all (left)**	1,3	2,4	0,0028	19
	**Ch_red_all (left)**	0,8	0,51	0,0005	52
	**Ch_red_all (right)**	0,7	0,38	0,0004	64
	**Ch_green_all (right)**	1	1,9	0,0022	18
	**Ch_blue_all (right)**	0,9	4,8	0,0061	6,5
	**Ch2_blue (right)**	1,2	2,0	0,0023	21
	**Ch2_green (right)**	1,8	3,7	0,0045	17
	**Ch2_red (right)**	1,5	2,7	0,0032	19

Tab. 6. The table shows the vertical illuminance values at the level of the user's cornea and the Circadian Light (CLA) values, and the effectiveness of the radiation in causing a circadian response (CS). The last column shows the values needed for a CS value of 0.05.

4.4. *Interpretation of the results*

The definition of a working threshold value for CL_A and CS is still debated. This is because many factors can influence the production of melatonin in addition to light stimulation, for example, from subjects' posture (Deacon and Arendt, 1994) to their diet (Peuhkuri, Sihvola and Korpela, 2012), from age-related differences in pre-retinal filtering (Herljevic *et al.*, 2005) to natural fluctuations in melatonin production (Arendt and Skene, 2005).

A study by Figueiro and Rea (Figueiro and Rea, 2013) tried to identify plausible threshold values, taking into account the intrinsic danger of an excessive alteration of circadian cycles, which might also be considered while using devices such as the stereoscopic visor.

The study presented the illuminance values for specific lighting sources necessary to obtain a circadian response of 0.05, 0.1, and 0.15 CS. This illumination was applied to the subjects' corneas using LEDs mounted on specially designed glasses. The subjects, who followed a specific preparation protocol, were subjected to light radiation for one hour. Through a blood sample before and after exposure to light, it was possible to observe the inhibition of melatonin production for different illuminance levels and different spectral components. For example, a CS value of 0.05 corresponds to a 5% reduction in melatonin in the bloodstream.

Observing the results obtained from the measurements at the IRCCS Institute of Neurological Sciences, Bellaria Hospital, we can assert that, although the data obtained by the software are in line with the circadian sensitivity curves of the cited studies, the illumination produced on the cornea by the stereoscopic visor is too low to cause a significant circadian reaction even in the hypothesis of exposure to radiation for one hour.

The last column in Table 6 shows the illuminance values/hour, which would be necessary for each sample to obtain a 5% reduction in melatonin in the bloodstream.

It is safe to say that the visor, used during daytime at the actual conditions, can be used for research purposes without causing shifts in the circadian cycle.

5. Further possible investigation

It has been shown (Glickman *et al.*, 2003) that the retinal ability to lead to the inhibition of melatonin is not uniform over the entire area covered by photoreceptors. The lower part gave blood melatonin inhibition results equal to those obtained on the whole retina, suggesting that the upper part is less sensitive to radiation regarding NIF processes. It is still unclear whether this difference is due to melanopsin in the mRGCs or the different concentrations of S-cones on the retinal carpet.

Since the measured stereoscopic viewer is equipped with OLED screens capable of generating different images, this could allow us to investigate, using appropriate levels of illuminance, the aspects related to the different sensitivity of the photoreceptors on the retina. For example, it would be possible to observe how the different spectral compositions of light can influence these differences.

6. Conflict of interest declaration

All authors wish to state that no financial or personal interests have affected the objectivity of this study and that no conflicts of interest exist.

7. Funding source declaration

This work was supported by the Italian Ministry of Health Lungotevere Ripa, 1 00153 - Roma (GR-2013-02358026 and GR-2019-12369242).

8. Short biography of the authors

Andrea Siniscalco - MSc in Design in 2002 and Ph.D. in 2007 in lighting fixture design. Since 2003, he has collaborated with the Lab Luce - Department of Design - Politecnico di Milano. Since 2008, he has been teaching lighting (design theory and CAD methods) as an adjunct professor at the School of Design - Politecnico di Milano. Deputy Director of the Masters in Lighting Design & Technology. Vice President of the GdC-Associazione Italiana Colore.

Caterina Tonon. MD, PhD. - Full Professor of Clinical Biochemistry and Molecular Biology, Neurologist, and Director of the Functional and Molecular Neuroimaging Unit, multidisciplinary team within the IRCCS Institute of the Neurological Sciences of Bologna. Her scientific activity is devoted to the implementation of advanced Magnetic Resonance Imaging techniques for clinical and research purposes.

Micaela Mitolo – Neuropsichologist, completed her PhD in the field of Neuroscience at University of Padua spending a period, as Visiting Ph.D., at University College London and University California San Diego. She is currently a Researcher at University of Parma and working at the IRCCS Institute of the Neurological Sciences of Bologna, exploring the neuroimaging correlated of clinical and neuropsychological impairments in neurodegenerative and neuro-oncology patients.

Claudia Testa - Professor of Physics at University of Bologna. She is a medical physicist with experience in acquisition and analysis of neuroimaging data. Her expertise concerns multiparametric data analysis for neurological disorders. Her work is also on the effect of light on brain activity at different wavelengths.

Marco Gaiani - Full Professor of Architectural Representation at University of Bologna, Dept. of Architecture, past Director of the INDACO Dept. of the Politecnico of Milano and DAPT Dept. of University of Bologna. A specialist in 3D computer imaging, modeling, and visualization for Heritage and architecture, he was one the first developers/user of laser scanning and automatic photogrammetry technologies in the Heritage field.

Maurizio Rossi - MSc, PhD. Full professor at Politecnico di Milano is the chair of the Lab. Luce, the Master in Lighting Design & Technology director, and member of the Ph.D. Design faculty. He directed 25 research-financed projects on topics related to light and color. 2012-18 he was the President of the GdC-Associazione Italiana Colore. Since 2018 member of the Executive Committee of AIC-International Color Association. Since 2022 vice-president of the AIC (president-elect 2024-25). Since 2021 he is member of the board of directors of the SID (Società Italiana Design).

Licensing terms

References

Arendt, J. and Skene, D. J. (2005) 'Melatonin as a chronobiotic', *Sleep Medicine Reviews*, 9(1), pp. 25–39. doi: 10.1016/j.smrv.2004.05.002.

Bandettini, P. A. *et al.* (1992) 'Time course EPI of human brain function during task activation', *Magnetic Resonance in Medicine*, 25(2), pp. 390–397. doi: 10.1002/mrm.1910250220.

Belenky, M. A. *et al.* (2003) 'Melanopsin retinal ganglion cells receive bipolar and amacrine cell synapses', *The Journal of Comparative Neurology*, 460(3), pp. 380–393. doi: 10.1002/cne.10652.

Bonsall, D. R. and Harrington, M. E. (2013) 'Circadian Rhythm Disruption in Chronic Fatigue Syndrome', *Advances in Neuroimmune Biology*, 4(4), pp. 265–274. doi: 10.3233/NIB-130074.

Brainard, G. C. *et al.* (2001) 'Action Spectrum for Melatonin Regulation in Humans: Evidence for a Novel Circadian Photoreceptor', *Journal of Neuroscience*, 21(16), pp. 6405–6412. doi: 10.1523/JNEUROSCI.21-16-06405.2001.

Castellano, A. *et al.* (2017) 'Functional MRI for Surgery of Gliomas', *Current Treatment Options in Neurology*, 19(10), p. 34. doi: 10.1007/s11940-017-0469-y.

Cedernaes, J., Schiöth, H. B. and Benedict, C. (2015) 'Determinants of shortened, disrupted, and mistimed sleep and associated metabolic health consequences in healthy humans', *Diabetes*, 64(4), pp. 1073–1080. doi: 10.2337/db14-1475.

Christoffersson, G. *et al.* (2014) 'Acute sleep deprivation in healthy young men: impact on population diversity and function of circulating neutrophils', *Brain, Behavior, and Immunity*, 41, pp. 162–172. doi: 10.1016/j.bbi.2014.05.010.

CIE (1986) 'CIE S001:1986, SO 10526/CIE S 005-1999 CIE Standard Illuminants for Colorimetry'. Commission Internationale de l'Eclaraige. Available at: https://cie.co.at/publications/colorimetric-illuminants (Accessed: 27 October 2021).

Dacey, D. M. and Packer, O. S. (2003) 'Colour coding in the primate retina: diverse cell types and cone-specific circuitry', *Current Opinion in Neurobiology*, 13(4), pp. 421–427. doi: 10.1016/S0959-4388(03)00103-X.

Davis, S., Mirick, D. K. and Stevens, R. G. (2001) 'Night Shift Work, Light at Night, and Risk of Breast Cancer', *JNCI Journal of the National Cancer Institute*, 93(20), pp. 1557–1562. doi: 10.1093/jnci/93.20.1557.

Deacon, S. and Arendt, J. (1994) 'Posture influences melatonin concentrations in plasma and saliva in humans', *Neuroscience Letters*, 167(1), pp. 191–194. doi: 10.1016/0304-3940(94)91059-6.

eMagin (2023) *eMagin*. Available at: https://emagin.com (Accessed: 24 March 2023).

Evangelisti, S. *et al.* (2021) 'Brain functional MRI responses to blue light stimulation in Leber's hereditary optic neuropathy', *Biochemical Pharmacology*, 191, p. 114488. doi: 10.1016/j.bcp.2021.114488.

Evans, J. A. and Davidson, A. J. (2013) 'Health consequences of circadian disruption in humans and animal models', *Progress in Molecular Biology and Translational Science*, 119, pp. 283–323. doi: 10.1016/B978-0-12-396971-2.00010-5.

Figueiro, M. G. and Rea, M. S. (2013) 'A Working Threshold for Acute Nocturnal Melatonin Suppression from "White" Light Sources used in Architectural Applications', *Journal of Carcinogenesis & Mutagenesis*, 04(03). doi: 10.4172/2157-2518.1000150.

Gall, D. (2004) 'Die Messung circadianer Strahlungsgrößen'. Technische Universität Ilmenau. Available at: https://www.tu-ilmenau.de/fileadmin/Bereiche/MB/lichttechnik/Literatur/2004/Vortrag_Gall2004.pdf (Accessed: 27 October 2021).

Glickman, G. *et al.* (2003) 'Inferior Retinal Light Exposure Is More Effective than Superior Retinal Exposure in Suppressing Melatonin in Humans', *Journal of Biological Rhythms*, 18(1), pp. 71–79. doi: 10.1177/0748730402239678.

Hattar, S. *et al.* (2002) 'Melanopsin-Containing Retinal Ganglion Cells: Architecture, Projections, and Intrinsic Photosensitivity', *Science*, 295(5557), pp. 1065–1070. doi: 10.1126/science.1069609.

Herljevic, M. *et al.* (2005) 'Light-induced melatonin suppression: age-related reduction in response to short wavelength light', *Experimental Gerontology*, 40(3), pp. 237–242. doi: 10.1016/j.exger.2004.12.001.

Kwong, K. K. *et al.* (1992) 'Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation.', *Proceedings of the National Academy of Sciences*, 89(12), pp. 5675–5679. doi: 10.1073/pnas.89.12.5675.

Kwong, K. K. (2012) 'Record of a single fMRI experiment in May of 1991', *NeuroImage*, 62(2), pp. 610–612. doi: 10.1016/j.neuroimage.2011.07.089.

La Morgia, C. *et al.* (2016) 'Melanopsin retinal ganglion cell loss in Alzheimer disease', *Annals of Neurology*, 79(1), pp. 90–109. doi: 10.1002/ana.24548.

La Morgia, C., Carelli, V. and Carbonelli, M. (2018) 'Melanopsin Retinal Ganglion Cells and Pupil: Clinical Implications for Neuro-Ophthalmology', *Frontiers in Neurology*, 9, p. 1047. doi: 10.3389/fneur.2018.01047.

LeGates, T. A., Fernandez, D. C. and Hattar, S. (2014) 'Light as a central modulator of circadian rhythms, sleep and affect', *Nature Reviews Neuroscience*, 15(7), pp. 443–454. doi: 10.1038/nrn3743.

Malik, S. *et al.* (2022) 'Understanding the significance of biological clock and its impact on cancer incidence', *Cancer Letters*, 527, pp. 80–94. doi: 10.1016/j.canlet.2021.12.006.

Mitolo, M. *et al.* (2018) 'Effects of Light Treatment on Sleep, Cognition, Mood, and Behavior in Alzheimer's Disease: A Systematic Review', *Dementia and Geriatric Cognitive Disorders*, 46(5–6), pp. 371–384. doi: 10.1159/000494921.

Mure, L. S. (2021) 'Intrinsically Photosensitive Retinal Ganglion Cells of the Human Retina', *Frontiers in Neurology*, 12, p. 636330. doi: 10.3389/fneur.2021.636330.

Ogawa, S. *et al.* (1992) 'Intrinsic signal changes accompanying sensory stimulation: functional brain mapping with magnetic resonance imaging.', *Proceedings of the National Academy of Sciences*, 89(13), pp. 5951–5955. doi: 10.1073/pnas.89.13.5951.

van Oosterhout, W. *et al.* (2018) 'Chronotypes and circadian timing in migraine', *Cephalalgia: An International Journal of Headache*, 38(4), pp. 617–625. doi: 10.1177/0333102417698953.

Ortuño-Lizarán, I. *et al.* (2018) 'Degeneration of human photosensitive retinal ganglion cells may explain sleep and circadian rhythms disorders in Parkinson's disease', *Acta Neuropathologica Communications*, 6(1), p. 90. doi: 10.1186/s40478-018-0596-z.

OSRAM Sylvania, Inc. (2019) *LED ColorCalculator*, *LED ColorCalculator*. Available at: https://www.osram.us/cb/tools-and-resources/applications/led-colorcalculator/index.jsp (Accessed: 27 October 2021).

Peuhkuri, K., Sihvola, N. and Korpela, R. (2012) 'Dietary factors and fluctuating levels of melatonin', *Food & Nutrition Research*. doi: 10.3402/fnr.v56i0.17252.

Phillips, M. L. (2009) ‘Circadian rhythms: Of owls, larks and alarm clocks’, *Nature*, 458(7235), pp. 142–144. doi: 10.1038/458142a.

Pringsheim, T. (2002) ‘Cluster Headache: Evidence for a Disorder of Circadian Rhythm and Hypothalamic Function’, *Canadian Journal of Neurological Sciences*, 29(1), pp. 33–40. doi: 10.1017/S0317167100001694.

Provencio, I. *et al.* (2000) ‘A Novel Human Opsin in the Inner Retina’, *The Journal of Neuroscience*, 20(2), pp. 600–605. doi: 10.1523/JNEUROSCI.20-02-00600.2000.

Rea, M. *et al.* (2012) ‘Modelling the spectral sensitivity of the human circadian system’, *Lighting Research & Technology*, 44(4), pp. 386–396. doi: 10.1177/1477153511430474.

Rea, M. S. *et al.* (2010) ‘Circadian light’, *Journal of Circadian Rhythms*, 8(0), p. 2. doi: 10.1186/1740-3391-8-2.

Rea, M. S., Bullough, J. D. and Figueiro, M. G. (2002) ‘Phototransduction for human melatonin suppression: Phototransduction for melatonin suppression’, *Journal of Pineal Research*, 32(4), pp. 209–213. doi: 10.1034/j.1600-079X.2002.01881.x.

Reiter, R. J. *et al.* (2012) ‘Obesity and metabolic syndrome: Association with chronodisruption, sleep deprivation, and melatonin suppression’, *Annals of Medicine*, 44(6), pp. 564–577. doi: 10.3109/07853890.2011.586365.

Rensselaer Polytechnical Institute (2020) *CS Calculator*. Available at: https://www.lrc.rpi.edu/cscalculator/ (Accessed: 27 October 2021).

Rosenthal, N. E. (2006) *Winter Blues: Everything You Need to Know to Beat Seasonal Affective Disorder*. Fourth Edition. New York: Guilford Press.

Rossi, M. (2019) *Circadian Lighting Design in the LED Era*. Springer International Publishing (Research for Development). doi: 10.1007/978-3-030-11087-1.

Schernhammer, E. S. *et al.* (2013) ‘Rotating Night-Shift Work and Lung Cancer Risk Among Female Nurses in the United States’, *American Journal of Epidemiology*, 178(9), pp. 1434–1441. doi: 10.1093/aje/kwt155.

Stevens, R. G. and Rea, M. S. (2001) ‘Light in the Built Environment: Potential role of Circadian Disruption in Endocrine Disruption and Breast Cancer’, *Cancer Causes & Control*, 12(3), pp. 279–287. doi: 10.1023/A:1011237000609.

Thapan, K., Arendt, J. and Skene, D. J. (2001) ‘An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans’, *The Journal of Physiology*, 535(1), pp. 261–267. doi: 10.1111/j.1469-7793.2001.t01-1-00261.x.

Vandewalle, G. *et al.* (2007) ‘Brain Responses to Violet, Blue, and Green Monochromatic Light Exposures in Humans: Prominent Role of Blue Light and the Brainstem’, *PLoS ONE*. Edited by S. He, 2(11), p. e1247. doi: 10.1371/journal.pone.0001247.

Vandewalle, G., Maquet, P. and Dijk, D.-J. (2009) ‘Light as a modulator of cognitive brain function’, *Trends in Cognitive Sciences*, 13(10), pp. 429–438. doi: 10.1016/j.tics.2009.07.004.

Yadav, A., Verma, P. and Singh, S. (2017) ‘Going beyond the limits: effect of clock disruption on human health’, *Biological Rhythm Research*, 48(5), pp. 693–700. doi: 10.1080/09291016.2017.1345428.

Application of a hyperspectral camera for colorimetric and spectroscopic measurements under natural light on outdoors artistic polychrome surfaces.

Filippo Cherubini[1], Andrea Casini[1], Costanza Cucci[1], Marcello Picollo[1], Lorenzo Stefani[1], Maurizio De Vita[2]

[1] *Istituto di Fisica Applicata "Nello Carrara" del Consiglio Nazionale delle Ricerche (IFAC-CNR), Italy. f.cherubini@ifac.cnr.it, a.casini@ifac.cnr.it, c.cucci@ifac.cnr.it, m.picollo@ifac.cnr.it, l.stefani@ifac.cnr.it*

[2] *Universita degli Studi di Firenze, Italy. maurizio.devita@unifi.it*

Corresponding author: Filippo Cherubini (f.cherubini@ifac.cnr.it)

ABSTRACT

The aim of this study is to define the parameters of accuracy of data acquired with the Specim IQ hyperspectral camera for CIE colorimetric measurements of polychrome surfaces in outdoor architectural settings with natural light. Furthermore, the study aims to compare the data obtained by the Specim IQ camera with those acquired by a contact colorimeter (Konica-Minolta CM-700d). CIE colorimetric measurements are generally acquired with dedicated instruments, such as tristimulus method colorimeters and spectrophotometric method, which require contact with the surface and coverage areas on the order of tens of mm2. The characteristics of requiring contact and analyzing very small areas can severely limit the study of artistic polychrome surfaces. This is because it may not always be possible to touch the analyzed surface and the measured areas may not necessarily be representative of a wider area of the same color. To overcome these limitations, one possible alternative is to use imaging techniques to acquire measurements from a distance while covering larger areas of the analyzed artifact. To calculate the colorimetric values as defined by the CIE and to also have the possibility to acquire spectroscopic data it was used the Specim IQ compact hyperspectral camera. This camera acquires 204 bands with a spectral resolution of 7 nm and an acquisition step of 3.5 nm in the 400-1000 nm operating range.

Colorimetric data were initially acquired on eight different color targets and two color palettes using a spectrocolorimeter. Subsequently, outdoor tests were conducted on the same samples under natural light using the Specim IQ hyperspectral camera. As a result, the operating characteristics of the hyperspectral camera for outdoor measurements aimed at studying the color of polychrome surfaces were defined.

KEYWORDS Hyperspectral imaging, polychromatic surfaces, natural light, Specim IQ, colorimetric analysis.

RECEIVED 07/05/2023; **REVISED** 18/07/2023; **ACCEPTED** 26/07/2023

1. Introduction

In the 1980s, a new technology called Imaging Spectroscopy (IS) was introduced, which has effectively revolutionized scientific research in the field of remote sensing of the Earth's surface (Goetz et al., 1985; Green et al., 1998). Specifically, the hyperspectral imaging (HSI) version of this technology allows for the acquisition of a nearly continuous sequence of spectroscopic images in contiguous, narrow spectral bands (bandwidth <10 nm) over an extended spectral range, generally from the visible (VIS, 400-750 nm) to the near-infrared (NIR, 750-2500 nm) (Cucci et al., 2016).

In recent years, the field of application of this technology has expanded into other areas, particularly in the field of cultural heritage, where it has been utilized for analyzing decorative elements, easel and wall paintings and even building facades (Casini et al., 2005; Kubik et al., 2007; Delaney et al., 2010; Ricciardi et al., 2012; Mounier et al., 2015; Cucci et al., 2016; Cucci et al., 2018a; Cucci et al., 2018b; Picollo et al., 2018; Amigo, 2019; Striova et al., 2020).

The HSI dataset, commonly referred to as a "cube-image" or "file-cube," contains a high level of information and can be processed using various algorithms depending on the desired final information (Nielsen 2015; Cucci et al., 2016, Luo et al., 2016; Deborah et al., 2019; Bai et al., 2019; Kleynhans et al., 2020; Cucci et al., 2021). This cube is a sequence of spectroscopic images that can provide the information typically given by traditional imaging techniques, such as infrared false color (IRFC), ratios between selected spectral images, and more. Additionally, the file-cube allows for the extraction of a reflectance spectrum from each pixel of the dataset, providing spectroscopic information that can be used to identify pigments and painting materials to some extent (Cucci et al., 2016). However, the potential of this technique is often limited by the complexity and cost of the instrumentation, software and hardware required to process the data, as well as the need for qualified technical personnel to interpret the data. Moreover, the equipment used in cultural heritage applications is often bulky and not suitable for outdoor use, making it difficult to adapt to different work environments.

In recent years, advancements in technology have made it possible to extend the use of hyperspectral technology outdoors, reducing and compensating for its previous limitations. The Specim IQ hyperspectral camera, developed by SPECIM Spectral Imaging Ltd. (Oulu, Finland, www.specim.fi), is one of the new imaging spectroscopy systems available for these applications, as presented in this work.

2. Specim IQ camera technical information

The Specim IQ is a hyperspectral imaging system designed to be used in various environments (Behmann et al., 2018). It differs from other hyperspectral imaging devices by its integration of color cameras, interchangeable data storage and batteries, data acquisition and processing electronics, and optimized operating system and user interface into a single portable housing.

The integrated RGB camera in the Specim IQ system permits to point the camera using a standard viewfinder image and manually adjust the focus of the hyperspectral camera. In addition, it is possible to check and process the acquired data using the camera back screen (like for common RGB cameras) and the processed data are storage in SD cards. This eliminates the need for additional computers, cabling, and power supplies making it easier for users to take advantage of this innovative technology.

The Specim IQ operates in the 400 – 1000 nm range recording spectra with 7 nm spectral resolution and 204 bands. The camera spatial resolution is of 512 x 512 pixels and from each pixel is possible to extract a spectrum. It saves both unprocessed and processed data, and the dimension of a single measurement is about 300 MB.

The operating system is user-friendly and guides the user through camera adjustments and data quality validations, eliminating the need for in-depth knowledge of hyperspectral imaging technology. The goal of the system design is to make hyperspectral imaging accessible to users who may not be familiar with it, enabling them to use it successfully in their applications.

Similar to most hyperspectral cameras, the Specim IQ data are acquired by performing a line scan over the target area. The camera is equipped with internal mechanisms for image scanning. However, since the process involves scanning to collect the image, it may take seconds or longer under normal conditions. Therefore, it is recommended to use Specim IQ with a standard tripod.

The Specim IQ allows for hyperspectral data acquisition under both outdoor and indoor conditions (Cucci et al., 2017; Behmann et al., 2018, Sciuto ed al., 2022), using either sunlight or artificial, broadband illumination souces. To calibrate the raw data the system is provided with a reflectance standard made of Spectralon®.

The Specim IQ camera allows for immediate visualization of hyperspectral data after the measurements, and users have the option to add metadata to them. The camera can be operated via PC with the Specim IQ Studio software. It can be used to control the camera and at the same time to process the IQ data as well as to create functions and models for processing the hyperspectral data. These models can be installed as applications to the Specim IQ camera to process the data and provide visualizations of the processing results for the user in real time without the need of a PC. The hyperspectral image data format is also compatible with most other hyperspectral data processing software available in the market.

The Specim IQ hyperspectral camera requires a white reference target to calibrate the data and obtain accurate reflectance spectra from the scene being measured. The white reference target should be a material with known diffuse reflectance, as spectrally constant as possible and close to 100%. The normalization operation can be performed in two ways:

- The white reference can be analyzed only once before all the other measurements (custom white reference). However, this approach requires that all the measurements are made under the same experimental conditions as that on the white reference.
- Alternatively, the white reference can be analyzed at the same time as the sample (concurrent white reference).

In addition, the camera allows to calibrate the data on the emission spectrum of a factory defined halogen light source.

After the reference target data have been obtained, each pixel data are normalized by referencing them to the white reference target. This normalization operation allows for accurate comparison of reflectance values between different pixels and different scenes.

3. Reasons for the research and definition of experimental parameters.

The Specim IQ camera offers significant advantages in terms of portability and versatility in comparison with most of the HSI devices available, making it a valuable analytical tool for various applications in the field of Cultural Heritage. Despite its usefulness, there are still some aspects that require clarification, particularly with regard to the use of quantitative measurements. In 2018 and 2019, two outdoor tests were conducted to evaluate the efficacy of the Specim IQ camera for colorimetric analysis in the architectural field.

During the analysis of the first test (Cucci et al., 2018), which was carried out at the minor historic village of Brozzi in Florence, problems emerged with the use of the camera in the presence of direct light. The second test (Cherubini et al., 2019), carried out at Piazza Santa Croce, aimed to compare different methodologies of color analysis in architecture, including RGB camera, spectrocolorimeter, color maquette, and Specim IQ hyperspectral camera. The obtained results were promising.

Finally, in 2021 (Cherubini et al., 2021), a test was also carried out in a controlled environment with a well-defined instrumental setup and artificial lighting, but issues still emerged with the type of setup used.

Despite this, all the tests performed have confirmed that this instrument can be used for colorimetric analysis in the architectural field. However, it is important to note that sufficient tests have not yet been conducted in an outdoor environment under natural light.

The motivation behind this research is to confirm the accuracy of data acquired by the Specim IQ camera for colorimetric calculations of polychromatic surfaces in outdoor architectural settings with natural light, such as building facades.

The polychromatic surfaces used for this study included:

- Eight certified Spectralon® Color Standards (Labsphere, New Hampshire, USA) with an approximate diameter of 3cm;
- Two mockups painted on a plaster support measuring 40x25x3cm, using colors from the Sikkens 4041 Color Concept Palette paints (https://www.sikkens.ch/it/colori/4041_color_concept), with chromes D6.10.30, F2.03.88, D6.35.55, E8.30.60, H2.03.82, and SN.02.77 (Figure 1a);
- Four samples of different stone materials commonly used in Florentine architecture, such as *pietra serena*, Carrara marble (Figure 1b), *pietra bigia*, and travertine, each of them measuring 25x25x5 cm.

These materials were arranged on an iron grid to be positioned on different wall backgrounds, as shown in figure 2. The results of the HSI analysis were then compared to data obtained from a Konica-Minolta CM700d spectrocolorimeter.

The acquisition setup for the data analysis campaign was configured as follows:

- The Specim IQ camera was mounted on a tripod at a distance of approximately 300 cm from the surface being analyzed (as shown in Figure 2).
- A set of eight Spectralon® Color Standards color samples, including nominal colors of red, orange, yellow, green, cyan, blue, violet, and purple, were used.
- Two mockups were created with the six different Sikkens paints, as previously reported.

- Four stone fragments made of materials commonly used in Florentine architecture were included.
- Measurement were performed with natural diffuse daylight between 09:00-11:00, with the polychrome samples arranged in the shade.
- A single operator was responsible for acquiring measurements at defined times.

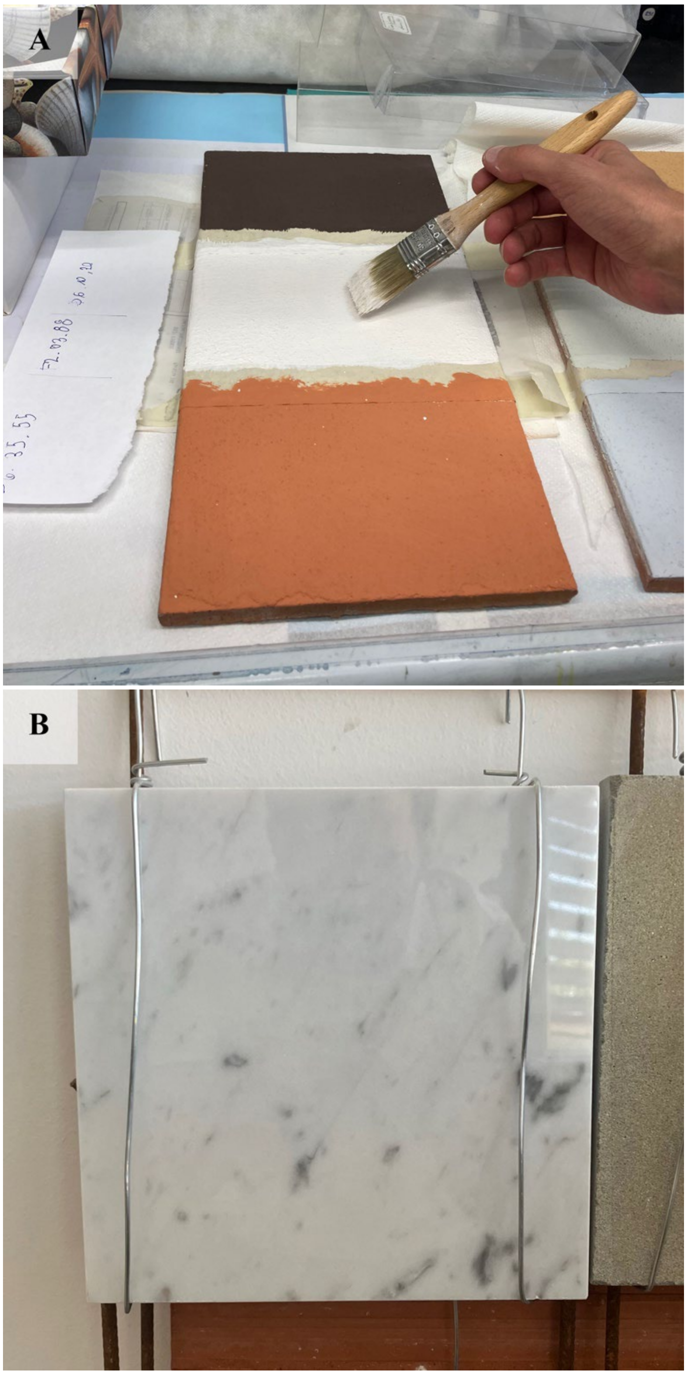


Fig. 1 – a)One of the two color palettes made using colors D6.10.30, F2.03.88, D6.35.55 from the Sikkens 4041 Color Concept palette. b) One stone sample of Carrara Marble.

Fig. 2 - Specim IQ camera arranged on a tripod at a distance of about 300 cm from the analysis surface.

All mockups and Spectralon® Color Standards color samples were arranged in the grid as shown in Figure 3.

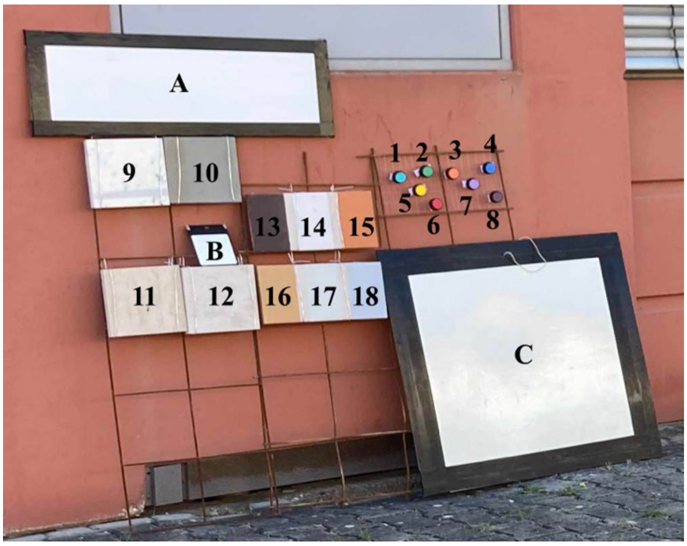


Fig. 3 – Mockups, stones and Spectralon® Color Standards arranged in the grid.

Legend: 1- Spectralon Cyan; 2- Spectralon Green; 3- Spectralon Orange; 4- Spectralon Blue; 5- Spectralon Yellow; 6- Spectralon Red; 7- Spectralon Violet; 8- Spectralon Purple; 9- Carrara Marble; 10-Pietra Serena; 11-Pietra Bigia; 12- Travertine; 13- Sikkens D6.10.30 Color ; 14- Sikkens F2.03.88 Color ;15- Sikkens E8.30.60 Color ;16- Sikkens D6.35.55 Color ;17- Sikkens H2.03.82 Color ;18- Sikkens SN.02.77 Color; A- Custom made white paint "Maimeri acrilico 018 - bianco di titanio" reference (not used for this test); B- White Spectralon reference; C- Custom made rutile titanium dioxide paint (not used for this test).

4. Data analysis

First, the samples were analyzed by using the Konica-Minolta CM-700d spectrocolorimeter. This instrumentation is equipped with an integrating sphere with a d/8° measurement geometry and works in the 400-700 nm range with an acquisition step of 10 nm. The light source and detector are a pulsed xenon lamp with a UV filter and silicon photodiodes, respectively. The instrument has its reference for white calibration (100% reflective) and a 'trap' for black calibration (0% reference). Measurements were taken using the 8-mm diameter measurement area accessory (MAV configuration) in diffuse reflectance configuration (SCE) excluding the specular component.

Due to the lack of homogeneous surface color in both the stone samples and the mockups, colorimetric analysis was conducted on five different points for each, as illustrated in Figure 4.

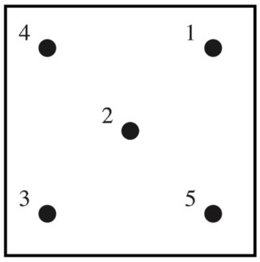


Fig. 4 – Scheme of the contact color measurements for the mockups and the stone samples.

Subsequently, an arithmetic average of the measured data was calculated to obtain a colorimetric average value for each sample. The L*a*b* values of the Sikkens paints on the mockups, and of the stone fragments are reported in Table 1 and 2, respectively.

	F2.03.88	**m.e.**	**D6.10.30**	**m.e.**	**D6.35.55**	**m.e.**	**E8.30.60**	**m.e.**	**SN.02.77**	**m.e.**	**H2.03.82**	**m.e.**
L*	93,27	±0,52	38,24	±1,4	61,53	±1,05	66,31	±0,3	80,74	±0,69	85,18	±0,35
a*	0,91	±0,33	4,95	±0,03	23,9	±0,35	9,82	±0,2	-0,83	±0,03	-1,66	±0,04
b*	4,17	±0,53	5,61	±0,18	31,57	±0,08	30,32	±0,34	-2,54	±0,12	5,25	±0,26

*Table 1 – Sikkens paints on the mockups L*a*b* values with the maximum error.*

	PIETRA SERENA	**m.e.**	**MARBLE**	**m.e.**	**PIETRA BIGIA**	**m.e.**	**TRAVERTINE**	**m.e.**
L*	60,71	±3,5	77,88	±1,81	82,42	±4,77	80,87	±0,78
a*	-0,53	±0,6	-0,76	±0,32	1,35	±0,68	2,23	±1,42
b*	10,13	±5,11	-1,83	±1,05	9,83	±2,82	13,41	±0,94

*Table 2 – Stone samples L*a*b* values with the maximum error.*

Then, "the maximum error" (m.e.) for each set of measurement was calculated. In this context, the "maximum deviation" or "maximum error" refers to the largest difference between the calculated average and each measured value of the set of data, indicating the maximum deviation found between the collected data and the reference value under consideration. If these data are carefully analyzed, it becomes evident that the paints applied on a plastered surface exhibit a more homogeneous distribution throughout the area. The maximum error found is approximately ±1.4, with an average value below ±0.5 for all L*a*b* coordinates. Instead, for the stones the value of the maximum error is significantly higher, reaching a maximum of ±5.11, with an average value of approximately ±2. This fact indicates that the stones have a less homogeneous surface than the paints under the chromatic aspect. This element is important to be considered when the colorimetric data are analyzed.

Regarding the data acquired with the IQ camera, they were recorded with an integration time of 20 milliseconds per band using the simultaneous white reference mode (concurrent white reference). Lastly, in order to apply the formulas of the International Commission on Illumination (Commission Internationale de l'Éclairage, CIE) using the data generated by the IQ camera for the analyzed objects, it was necessary to interpolate the spectral sampling interval of the hyperspectral data from 3.5 nm to 1 nm. This was achieved using a program developed specifically at IFAC-CNR, which, upon completion of the process, provides gray-scale TIF images of the three L*, a*, and b* coordinates (CIELab76 color space) for the standard observer 2° and illuminant D65.

The L*a*b* values calculated for the Labsphere color targets, painted mockups, and stone samples, contained in the TIF format files, were managed and processed using the Adobe Photoshop® program. The 'eyedropper' tool was used to acquire the L*a*b* values of the TIF files. The 'eyedropper' tool in Photoshop is used for color sampling and color picking. this tool allows you to click on any pixel within an image and it will sample the color of that pixel. Due to the low resolution of the image, the 'eyedropper' tool was used with the 'medium' mode to obtain the L*, a*, and b* values by selecting a square of 3x3 pixels in the sample.

when we use the 'eyedropper' tool with a 3x3 pixel area means that when we click on a pixel in the image, Photoshop will not only sample the color of that exact pixel but also include the colors of the surrounding 9 pixels (3x3 square area) in the average calculation. By considering a 3x3 pixel area, the tool helps reduce the impact of isolated color outliers and provides a more accurate representation of the color within that small region of the image. The 'medium' mode refers to the way Photoshop calculates the color average. In this mode, Photoshop calculates the median value for each color channel (L*, a*, b*) within the 3x3 pixel area. The median value is the middle value when all the values are arranged in numerical order. This method helps minimize the impact of extreme color values and produces a more balanced color representation. Using the 'eyedropper' tool with a 3x3 pixel area and medium mode is particularly useful in situations where you want to obtain a more stable and representative color reading, especially in images with noise or small color variations. It's worth noting that when using the 'eyedropper' tool in Photoshop, there are significant limitations imposed on the L*, a*, and b* values: Photoshop displays these values only as integers, eliminating any decimal points (Figure 5).

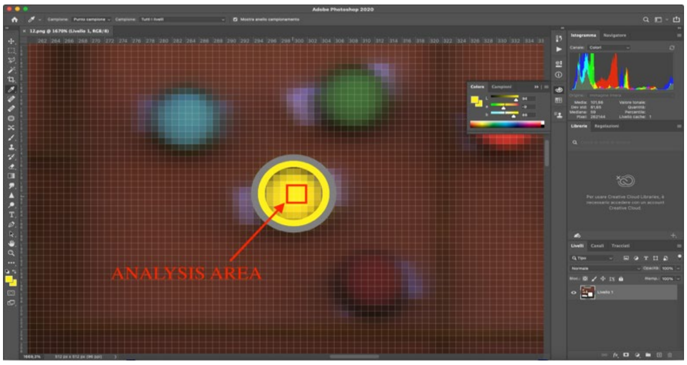


Fig. 5 – Measurement IQ-925. Colorimetric values for targets calculated with Adobe Photoshop® software.

However, this work mainly focused on defining the accuracy of the measurement system, Specim IQ hyperspectral camera, under daylight measurement conditions. The primary objective was to verify the accuracy of measurements by calculating colorimetric parameters.

The data obtained were reported in Table 3.

	CM700d	IQ-923	IQ-924	IQ-925
Analysis area in px	*	3x3	3x3	3x3
Degrees	*	0	0	0
Distance in cm	*	300	300	300
Violet	63.77, 18.45, -22.42	62, 17, -15	62, 17, -15	62, 17, -15
Purple	43.78, 14.94, -5.05	44, 15, 0	44, 15, 0	44, 15, 0
Yellow	87.39, 3.02, 84.67	85, 6, 81	85, 7, 82	85, 6, 81
Orange	69.77, 45.35, 40	68, 45, 40	68, 45, 40	69, 46, 40
Cyan	71.95, -27.92, -11.38	68, -24, -6	68, -24, -5	68, -25, -5
Blue	57.61, 3.06, -43.06	56, 2 ,-35	56, 2 ,-35	56, 2 ,-35
Red	49.65, 50.88, 23.95	51, 48, 23	51, 49, 23	51, 48, 22
Green	62.76, -30.42, 15.52	61, -25, 17	61, -25, 17	61, -25, 17
D6.10.30	36, 6, 9	40, 5, 7	40, 5, 7	40, 5, 7
F2.03.88	94, 1 ,6	93, 1, 8	93, 1, 8	93, 1, 8
D6.35.55	61, 26, 35	62, 24 ,33	62, 24 ,33	62, 24 ,33
E8.30.60	66, 13, 34	66, 10, 31	67, 10, 31	66, 10, 31
H2.03.82	88, -1, 4	84, 0, 8	85, 0, 8	84, 0, 8
SN.02.77	83, -1, -2	80, 0, 0	81, 0, 0	81, 0, 0
Pietra serena	60.71, -0.53, 10.13	62, 0, 12	63, 0, 11	63, 0, 11
Carrara Marble	77.88, -0.76, -1.83	83, 0, 6	83, 0, 6	83, 0, 6
Pietra bigia	82.42, 1.35, 9.83	81, 2 ,13	82, 3 ,14	81, 2 ,13
Travertine	80.87, 2.23, 13.41	79, 3, 16	79, 4, 17	80, 4, 17

*Table 3 - L*a*b* values calculated from measurements acquired with the Specim IQ camera*

The data obtained were divided into three homogeneous groups, namely Spectralon® Color Standards, mockups, and stone samples and the following results can be highlighted:

- All eight certified Spectralon® Color Standards were strongly influenced by the spatial resolution of the acquired data due to the distance of the camera (300 cm); in fact, the external pixels of the targets are partially affected by the background wall color that resulted to be mixed with the targets' colors (Figure 6).
- The mockups showed a sufficient agreement with the expected colorimetric values except the dark brown D6.10.30 and the light gray H2.03.82 paints;
- The stone materials presented the most critical issues, as expected, due to their natural surface variability. The lack of chromatic homogeneity of the surface made the colorimetric analysis challenging. However, for the more homogeneous samples such as *pietra serena*, *pietra bigia* and travertine, results comparable to those obtained with contact instrumentation were achieved. Carrara marble, on the other hand, showed greater chromatic dissimilarities.

It should be remembered, however, that the Adobe Photoshop® program displays only integer values for the L*a*b* color space. This introduces an additional factor of error that has to be considered when analyzing the data.

The software Adobe Photoshop® was selected due to its extensive usage and popularity as a commercial software that ensures accurate analysis of L*a*b* values without introducing errors. According to the research reported in the paper "Application of a hyperspectral camera for colorimetric measurements on polychrome surfaces in a controlled environment and evaluation of three image processing software for displaying colorimetric data: Pros and cons of the methodology presented" (Cherubini et al., 2023), other freely available software, such as GIMP, demonstrated inconsistent value, particularly regarding the b* parameter.

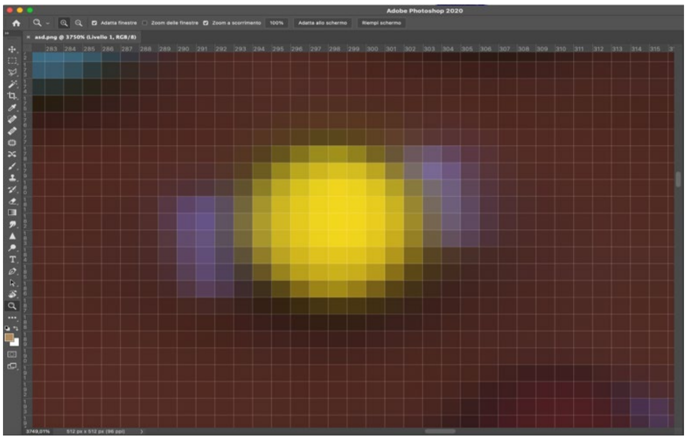


Fig. 6 - The external pixels of the Yellow target affected by the background wall color

5. Conclusion

From what emerged in this preliminary study designed to verify the characteristics of the Specim IQ hyperspectral camera applied in an outdoor environment for colorimetric analysis of non-self-luminous objects, it can be said that the system has interesting properties for this application.

Considering the instrumental setup and the adopted lighting conditions, the Specim IQ camera, as described in the data analysis, exhibited a good response in terms of colorimetric calculation for painted surfaces on mockups. However, the colorimetric calculation of the stones presented more critical issues. In conclusion, we can affirm that the Specim IQ camera demonstrated a positive response.

However, further testing under more challenging measurement conditions and in the presence of more environmental variables will be required to fully evaluate its capabilities.

6. Conflict of interest declaration

All authors of the Color Culture and Science Journal (CCSJ) are requested to disclose any actual or potential conflict of interest including financial, personal, or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, their work. The Conflict of interest declaration must be included in the paper and states if no financial/personal interests have affected the author's objectivity(s) or, if there are, the source and nature of the potential conflicts. Authors must state explicitly whether potential conflicts do or do not exist.

7. Funding source declaration

All authors are requested to provide a declaration of any funding or research grants (and their source) received in the study, research, or assembly of the manuscript. Authors are requested to identify who provided financial support for the research and/or preparation of the article and briefly describe the sponsor's role(s) if any. If the funding source(s) had no such involvement, then this should be stated.

8. Short biography of the author(s)

Filippo Cherubini - Filippo Cherubini is a technician at the Sabec group. He has a Bachelor of Science degree in Architecture and two postgraduate course at the University of Florence. His interests include environmental restoration and architectural color studies.

Andrea Casini - Andrea Casini, MSc graduated in Physics from the University of Florence on 1968, has worked extensively on the digital processing of both biomedical and non destructive testing images as a researcher at IFAC-CNR. Since 1990, he has been working on optical hyperspectral imaging equipment in the Cultural Heritage field, mainly on paintings, and on the processing of their data. After retirement, he maintains an external collaboration with IFAC-CNR.

Costanza Cucci - Costanza Cucci graduated in Physics and got her PhD in Conservation Science from the University of Florence (Italy). She is permanent researcher at the Institute of Applied Physics "Nello Carrara" of the Italian National Research Council (IFAC-CNR) of Florence, where she has carried on her research activity since 2000 in different applicative areas of photonic and applied spectroscopy (cultural heritage, environmental monitoring, safety/quality controls in foods, optical sensors). Her current research interests are mainly in hyperspectral imaging with a focus on applications on Cultural Heritage; spectroscopic data-analysis and processing with a focus on multivariate/statistical techniques; museum lighting (monitoring, preventive conservation, and guidelines)

Marcello Picollo - Marcello Picollo, PhD in Photonics from the University of Eastern Finland (UEF), Faculty of Science and Forestry, Joensuu (Finland) and graduated in geology from the University of Florence, is a researcher at the Institute of Applied Physics "Nello Carrara" of the National Research Council of Italy (IFAC-CNR), Florence. He has been working on spectroscopic investigations of works of art since 1991 and his main research focus is on artists' material characterization using non-invasive spectroscopic and imaging techniques

Lorenzo Stefani - Lorenzo Stefani is a technician in telecommunications at IFAC-CNR. He is in charge of the development of hardware and software for computer-controlled instrumentation for the non-invasive and in situ study of artworks.

Maruzio De Vita - Maurizio De Vita is a Full Professor at the University of Florence department of Architecture, and the Director of the School of Specialization in Architectural and Landscape Heritage at the Department of Architecture, at the same university. He has taught at Columbia University in New York, Syracuse University, IUAV Faculty of Architecture in Venice, Beijing University of Civil Engineering and Architecture in Beijing, and South-East University in Nanjing. Additionally, he is a co-owner of Studio De Vita & Schulze Architetti, an architectural firm based in Florence and Beijing. De Vita has been involved in the design and supervision of numerous restoration projects worldwide, encompassing historic and artistic buildings, monumental complexes, city walls, historic parks, and gardens, both in Italy and abroad.

Licensing terms

References

Amigo, J. M. (2019) *Hyperspectral Imaging, Volume 32 - 1st Edition*. Elsevier.

Bai, D., Messinger, D. W. and Howell, D. (2019) 'A hyperspectral imaging spectral unmixing and classification approach to pigment mapping in the Gough & Selden Maps', *Journal of the American Institute for Conservation*, 58(1–2), pp. 69–89. doi: 10.1080/01971360.2019.1574436.

Behmann, J. et al. (2018) 'Specim IQ: Evaluation of a New, Miniaturized Handheld Hyperspectral Camera and Its Application for Plant Phenotyping and Disease Detection', Sensors, 18(2). doi: 10.3390/s18020441.

CIE Publication No 15.2, 1986. Colorimetry (2nd edition); Commission International de l'Eclairage (CIE), Central Bureau of the CIE: Vienna, Austria.

CIE 15:2004, 2004. Technical Report. Colorimetry, 3rd ed.; Commission International de l'Eclairage (CIE), Central Bureau of the CIE: Vienna, Austria.

Cucci, C. *et al.* (2017) 'Bridging research with innovative products: a compact hyperspectral camera for investigating artworks: a feasibility study', in *Optics for Arts, Architecture, and Archaeology VI*. *Optics for Arts, Architecture, and Archaeology VI*, SPIE, pp. 17–29. doi: 10.1117/12.2270015.

Cucci, C. *et al.* (2018) 'The illuminated manuscript Corale 43 and its attribution to Beato Angelico: Non-invasive analysis by FORS, XRF and hyperspectral imaging techniques', *Microchemical Journal*, 138, pp. 45–57. doi: 10.1016/j.microc.2017.12.021.

Cucci, C. *et al.* (2018) 'Potentialities of reflectance hyperspectral imaging technique in the field of architecture', in *Colour and Colorimetry Multidisciplinary Contributions*. *14th Color Conference*, Firenze: Veronica Marchiafava, Lia Luzzato, pp. 155–166.

Cucci, C. *et al.* (2021) 'Reflectance hyperspectral data processing on a set of Picasso paintings: which algorithm provides what? A comparative analysis of multivariate, statistical and artificial intelligence methods', in

Groves, R. and Liang, H. (eds) *Optics for Arts, Architecture, and Archaeology VIII*. *Optics for Arts, Architecture, and Archaeology (O3A) VIII*, Online Only, Germany: SPIE, p. 1. doi: 10.1117/12.2593838.

Cherubini, F. *et al.* (2019) 'The survey of color in architecture: comparison between new and old methodologies', in *Color and Colorimetry Multidisciplinary Contributions*. *15th Color Conference*, Macerata: Aldo Bottoli, Veronica Marchiafava, pp. 23–27.

Cherubini, F. *et al.* (no date) 'Application of hyperspectral camera and spectrocolorimeter for spectroscopic and colorimetric measurements on polychrome surfaces in a controlled environment: pros and cons of the presented technologies', in International Colour Association (AIC) Conference 2021 Milano: AIC, pp. 745–749.

Cherubini, F. *et al.* (2023) 'Application of a hyperspectral camera for colorimetric measurements on polychrome surfaces in a controlled environment and evaluation of three image processing software for displaying colorimetric data: Pros and cons of the methodology presented', *Color Research & Application*, 48(2), pp. 210–221. doi: 10.1002/col.22835.

Deborah, H., George, S. and Hardeberg, J. Y. (2019) 'Spectral-divergence based pigment discrimination and mapping: A case study on The Scream (1893) by Edvard Munch', *Journal of the American Institute for Conservation*, 58(1–2), pp. 90–107. doi: 10.1080/01971360.2018.1560756.

Delaney, J. K. *et al.* (2010) 'Visible and infrared imaging spectroscopy of Picasso's Harlequin musician: mapping and identification of artist materials in situ', *Applied Spectroscopy*, 64(6), pp. 584–594. doi: 10.1366/000370210791414443.

ISO/CIE 10526, 1991. CIE standard colorimetric illuminants, International Organization for Standardization, Geneva (CH).

ISO/CIE 10527, 1991. CIE standard colorimetric observers, International Organization for Standardization, Geneva (CH).

Kleynhans, T. *et al.* (2020) 'An alternative approach to mapping pigments in paintings with hyperspectral reflectance image cubes using artificial intelligence', *Heritage Science*, 8(1), p. 84. doi: 10.1186/s40494-020-00427-7.

Kubik, M. (2007) 'Chapter 5 Hyperspectral Imaging: A New Technique for the Non-Invasive Study of Artworks', in Creagh, D. and Bradley, D. (eds) *Physical Techniques in the Study of Art, Archaeology and Cultural Heritage*. Elsevier (Physical Techniques in the study of Art, Archaeology and Cultural Heritage), pp. 199–259. doi: 10.1016/S1871-1731(07)80007-8.

Luo, G. *et al.* (2016) 'Minimum Noise Fraction versus Principal Component Analysis as a Preprocessing Step for Hyperspectral Imagery Denoising', *Canadian Journal of Remote Sensing*, 42(2), pp. 106–116. doi: 10.1080/07038992.2016.1160772.

Mounier, A. and Daniel, F. (2015) 'Hyperspectral imaging for the study of two thirteenth-century Italian miniatures from the Marcadé collection, Treasury of the Saint-Andre Cathedral in Bordeaux, France', *Studies in Conservation*, 60(sup1), pp. S200–S209. doi: 10.1179/0039363015Z.000000000225.

Oleari, C. (2016) *Standard colorimetry: definitions, algorithms, and software*. Chichester, West Sussex, UK: John Wiley & Sons, Inc.

Picollo, M. *et al.* (2020) 'Hyper-Spectral Imaging Technique in the Cultural Heritage Field: New Possible Scenarios', *Sensors*, 20(10), p. 2843. doi: 10.3390/s20102843.

Ricciardi, P. *et al.* (2012) 'Near Infrared Reflectance Imaging Spectroscopy to Map Paint Binders In Situ on Illuminated Manuscripts', *Angewandte Chemie International Edition*, 51(23), pp. 5607–5610. doi: 10.1002/anie.201200840.

Sciuto, C. *et al.* (2022) 'What Lies Beyond Sight? Applications of Ultraportable Hyperspectral Imaging (VIS-NIR) for Archaeological Fieldwork', *Journal of Field Archaeology*, 47(8), pp. 522–535. doi: 10.1080/00934690.2022.2135066.

Sharma, G., Wu, W. and Dalal, E. N. (2005) 'The CIEDE2000 color-difference formula: Implementation notes, supplementary test data, and mathematical observations', *Color Research & Application*, 30(1), pp. 21–30. doi: 10.1002/col.20070.

Signoroni, A. *et al.* (2020) 'Spatial–Spectral Evidence of Glare Influence on Hyperspectral Acquisitions', *Sensors*, 20(16), p. 4374. doi: 10.3390/s20164374.

Striova, J., Dal Fovo, A. and Fontana, R. (2020) 'Reflectance imaging spectroscopy in heritagescience', *La Rivista del Nuovo Cimento*, 43(10), pp. 515–566. doi: 10.1007/s40766-020-00011-6.

Leonetto Cappiello and Jean d'Ylen's posters: colour takes centre stage

Marcello Scalzo[1]

[1] *Department of Architecture, University of Florence, Florence, Italy, marcello.scalzo@unifi.it*

ABSTRACT

Undoubtedly, Frenchmen Jules Cheret and Henri Toulouse Lautrec laid the foundations of modern poster art. At the end of the 19th century, street walls were covered with bright, eye-catching, and colourful posters: the hurried and distracted passer-by was attracted by seductive and dynamic figures in bright colours. At the beginning of the 20th century, the advertising poster spread in France thanks to a few Parisian printing houses, including Imprimerie Établiments Vercasson and Maison Devambez, among the first actual advertising agencies. In 1900, the Leghorn-born Leonetto Cappiello, then a naturalised Frenchman, made his debut as 'Maître affichiste' in the Vercasson printing house for a collaboration that was to last until the advent of the First World War; his place, from 1919, was taken by Jean d'Ylen, until then practically unknown. Cappiello's prestige, quality and competence are unavoidable, but the many aspects they have in common are undeniable. Both draw their subjects with a comic, almost caricature-like verve, figures full of dynamism, reminiscent of photographic snapshots, but above all, the colour choices unite them. It is colour that permeates their advertisements: their characters stand out against the dark background of the scene, and from the black experiences emerge figures in brightly coloured clothes, playing with the contrasts of complementary colours. Red and green, blue and orange, and white with barely noticeable yellow brush strokes stand out against the black background, as do the lettering in a yellow ranging from lemon to intense chrome. Their colour choices are free and extrovert, vermilion elephants, red or green horses, animals, plants, and objects in the most varied shades, almost all unconventional: colour becomes the protagonist.

KEYWORDS Leonetto Cappiello, Jean d'Ylen, French poster designers, Billboards

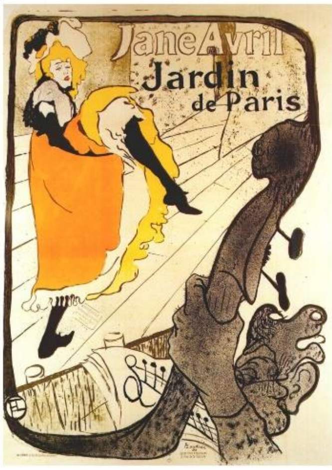
RECEIVED 08/03/2023; **REVISED** 27/07/2023; **ACCEPTED** 01/08/2023

1. Introduction: French advertising graphics in the second half of the 19th century

The appearance of the first colour advertising posters in the second half of the 19th century was due to the perfection of the chromolithography technique of which, in France, the undisputed prime mover was undoubtedly Jules Chéret. His posters are distinguished by the high pictorial rendering that gives his works intense colour effects ranging from animated backgrounds to transparent glazes. Henri de Toulouse-Lautrec deserves a special mention: his posters are characterised by an essential graphic language, sharp contours and evenly spread colours, whose style can be traced back to the most advanced artistic research of the late 19th century.
However, at the turn of the century, the expressive graphics of Chéret and Lautrec were counterbalanced by a group of authors, expressions of what has been defined as the '20th-century style', characterised by drawings imbued with lightness and redundancy [1].

In the French sphere, one recognises that linked to Art Noveau, the leading creator of which was Adolphe Mucha, followed by equally prominent artists such as Eugene Grasset, Louis Théophile Hingre and Henri Privat Livemont.

At the same time, but outside France, we recognise another Mitteleuropean matrix, that of the Jugendstil, with leading artists such as Koloman Moser, Alfred Roller and Gustav Klimt. Finally, let us remember the Italian Art Nouveau poster designers, such as Aleardo Terzi, Giovanni Maria Mataloni and Adolf Hohenstein, followed by Marcello Dudovich and Leopoldo Metlicovitz.



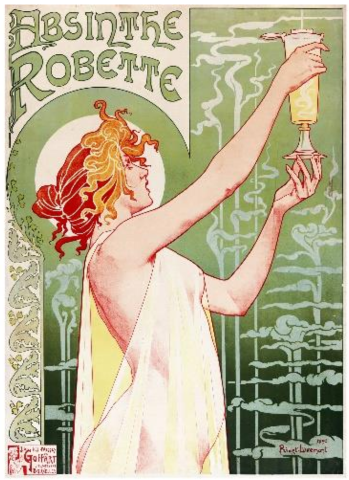


Fig. 1. Jules Chéret, Folies Bergère, 1893; Fig. 2. Henri de Toulouse-Lautrec, Jane Avril, 1893; Fig. 3. Adolphe Mucha, Biscuits Lefevre, 1896; Fig. 4. Henri Privat Livemont, Absinthe Robette, 1896.

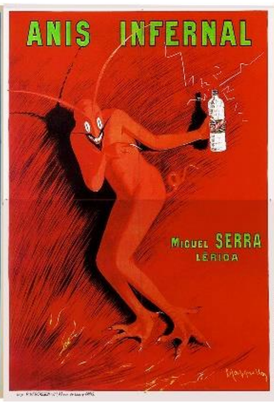


Fig. 5. Leonetto Cappiello, Chocolat Klaus, 1903; Fig. 6. Leonetto Cappiello, Anis Infernal, 1905; Fig. 7. Leonetto Cappiello, Maurin quina, 1906; Fig. 8. Leonetto Cappiello, Pineral, 1912.

2. Advertising in France at the beginning of the 20th century

Paris, at the beginning of the 20th century, is known to everyone as the 'Ville Lumière': in fact, it is one of the first European metropolises to equip itself with public street lighting. Moreover, the French capital is the must-visit destination for artists, musicians and writers who find in the city a particularly fertile environment for creative activities, an ideal climate for innovative movements and artistic avant-gardes: it is completely useless (and almost impossible) to list the numerous personalities orbiting the French capital in those years.

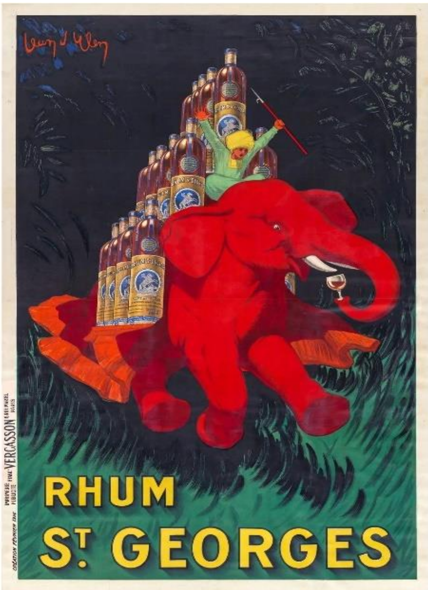
1900 is the year of the great Universal Exhibition and the Paris Olympics; the city has almost two million inhabitants and is experiencing an enormous wave of economic and social development; production and consumption are on the rise and, in parallel, new companies and brands appear, new consumer products and materials.

There was a need to publicise these new products and to relaunch existing ones; to meet this increased need for communication, print shops and advertising agencies were created or strengthened: essential companies such as Devambez, Star, Dam, Publicis, Synergie and Vercasson operated in Paris. The Italian agency Maga, one of the most renowned of the time, opened a branch in the French capital in 1920; other paramount companies, such as, for example, Publivox in Geneva, Ricordi in Milan, and Chappuis in Bologna, had correspondents there.

Big brands demanded advertiser posters that could generate strong emotional reactions in consumers and, at the same time, convey positive, simple, and compelling messages.

The power of the image, sometimes of a slogan accompanying the poster, became an essential chapter in the history of collective communication: these were the premises of the excellent mass dissemination that would characterise the modern era.

The images of the way of life in the first decades of the last century, proposed by the posters, depict an idyllic, carefree lifestyle, combining happiness and consumption, as shown by the expressions on the always smiling faces of the young girls portrayed in the posters. Excellent and effective advertising should arouse desires for consumption or possession, new life habits aimed at profoundly transforming everyday life in record time.



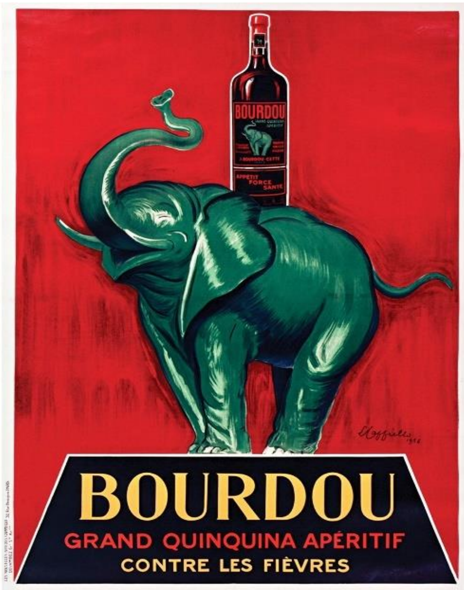


Fig. 9. Leonetto Cappiello, Végétaline, 1928 – Fig. 10. Jean d'Ylen, Rhum St. Georges, 1926 - Fig. 11. Leonetto Cappiello, Bourdou, 1926.

3. Leonetto Cappiello

Leonetto Cappiello (Leghorn 1875 - Cannes 1942) arrived in France in 1898; within a few years, the artist's work would have created a kind of watershed in the field of advertising graphics: Cappiello, following in the footsteps of Chéret and Toulouse-Lautrec, introduced into the world of 'affichés' a modern, incisive and synthetic language, with essential graphics, decidedly detached from the, albeit appreciated, but overabundant 'decorative ornamentation' that characterised Art Noveau posters.

From the early decades of the 20th century, Leonetto Cappiello became a point of reference for many artists; his innovative ideas would influence the creations of numerous poster artists of the following generations. He became a French citizen in 1930 and was awarded the Legion of Honour in 1914.

In November 1900, Cappiello signed his first contract with the 'Etablissements Vercasson'. At that time, the typographer's role was not only to have posters made but also to act as an advertising agent. Therefore, the customer who wanted a poster often contacted the printer, who found the most appropriate poster designer.

Until 1916, all but four of Cappiello's posters came off the presses of the Vercasson printing house [2]; some 3,000 posters and many sketches are attributed to him. In 1911, he was 'Maîtres de l'affiche' and signed a second contract with Vercasson regulating not only the economic conditions but also the number of works he had to supply: 'Mr Cappiello will have to supply Mr Vercasson, and Mr Vercasson will have to order and accept five sketches for at least one month for the creation of posters. Mr. Vercasson also undertakes to order from Mr. Cappiello and to accept, and the latter to supply him monthly with a minimum of four large-format models of approximately one metre and forty centimetres in enlargement of the sketches already supplied, a total of 55 sketches and 44 models during the year" (AA.VV., 1981, p. 114). Sometimes in Cappiello's sketches, there was no link between the product for sale and the subject of the sketch, which meant that a rejected drawing could, with a few modifications, be reused for another client.

With the outbreak of war in 1914, Cappiello abandoned Vercasson [3]; in 1919, he set up his own company 'Affiches Cappiello', granting the publisher Devambez exclusive rights to his new works; in 1921, he signed a new contract with them until 1936. In addition to the print shop, Devambez owned an art gallery where Cappiello held an important exhibition of posters and sketches in 1923. Then, in 1937, he joined forces with the publisher Damour. Around 1940 he moved to the south of France to Grasse; he died in Cannes in 1942 following an illness.

Fig. 12. Leonetto Cappiello, Florio Cinzano, 1930; Fig. 13. Jean d'Ylen, Shell, 1927; Fig. 14. Jean d'Ylen, Shell, 1930.

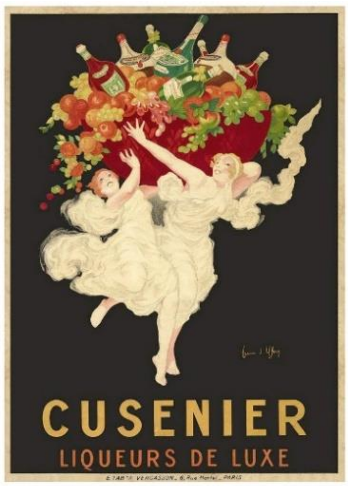


Fig. 15 - Leonetto Cappiello, Contratto, 1922; Fig. 16 - Leonetto Cappiello, Cognac Monnet, 1927; Fig. 17. Jean d'Ylen, Sandeman's, 1925; Fig.18. Jean d'Ylen, Cusenier, 1924.

4. Jean d'Ylen

Jean-Paul Béguin (Paris 1886-1938), pseudonym of Jean d'Ylen, was a French painter and illustrator mainly active between 1920 and 1930. He attended the Bernard Palissy Ecole, a Parisian school of Applied Arts and later L'École des Beaux-Arts, where he became a pupil of the painter Fernand Cormon. Before entering the advertising world, he tried his hand as a landscape painter, jewellery designer, decorative painter, and cartographer during the Great War. Towards the end of the first decade of the 20th century, he embarked on a career as a poster artist in Pierre Vercasson's print shop, succeeding Cappiello as "Maîtres de l'affiche" in 1922 [4]; from him derived shapes and colours and that exotic imagery typical of the Leghorn artist's posters. The latter had left numerous sketches to Vercasson under contract: it cannot be excluded that Jean d'Ylen reworked Cappiello's sketches for some signs.

From 1934 onwards, following disagreements with Vercasson, he worked directly with the Weiner agency in London, going so far as to disseminate his posters in Europe and the United States. When he was at the peak of his career, death caught him prematurely in 1938.

Fig. 19 - Leonetto Cappiello, Longines, 1927; Fig. 20. Jean d'Ylen, Zenith, 1928; Fig. 21. Leonetto Cappiello, Barbier Dauphin, 1937; Fig. 22. Jean d'Ylen, Filver, 1926.

5. Colour the posters of Leonetto Cappiello and Jean d'Ylen

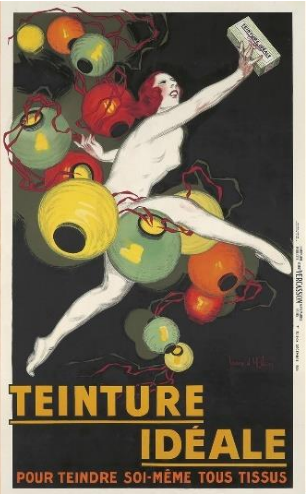
The 1903 Chocolat Klaus poster marks a milestone in Leonetto Cappiello's career, which he called 'the second stage of my evolution' [5]: inaugurates the dark background, the dissonance of colour planes, and the contrast of pure colours.

The poster must stand out on the wall, impose itself on its surroundings, and be a 'visual shock' to the beholder. In the advertising scene for his audacity, Cappiello is defined as a forerunner of the Fauves' painting; in his 1910 article, critic Camille Mauclair described his posters as follows: "Cobalt blues, phosphoric yellows, blinding vermilion, purples and blacks, oranges and greens vibrate, clash, struggle and panic in struggles and unlikely alliances" [6].

Cappiello often expresses simplicity through an association of ideas and images suggested by the product's name: as in Anis infernal (1905) depicts a red devil in his burning hell, with the lettering in green, the complementary colour. In Pineral (1912), the black background enhances the yellow lettering, the orange tree, and the red devil, which in Maurin Quina (1906) is coloured a glowing green. Sometimes what arouses curiosity, what attracts the observer, is not, for example, the exotic animal, unrelated to the product to be advertised, but the colour with which it is portrayed: like the elephants in Vegetaline (1928), Bourdou's (1926) or Jean d'Ylen's Rhum St. Georges (1926). Fancifully coloured animals: Cappiello's zebras for Florio Cinzano (1930) or the decidedly surreal mechanical horses for Shell by Jean d'Ylen (1927 and 1930).

Jean d'Ylen often takes up the style and spirit of the early Cappiello posters, characterised by imaginary, cheerful, costumed characters, or pierrot, clowns and circus performers, painted in bright colours against a dark, black, blue, or deep red background.

Joyful maidens seem to dance in Cappiello's posters for Contratto (1922) and Cognac Monnet (1927); they find compositional and chromatic correspondences (the black background and the abundance of yellows) with those of Jean d'Ylen's Port Sandeman (1925) and Cusenier (1924).



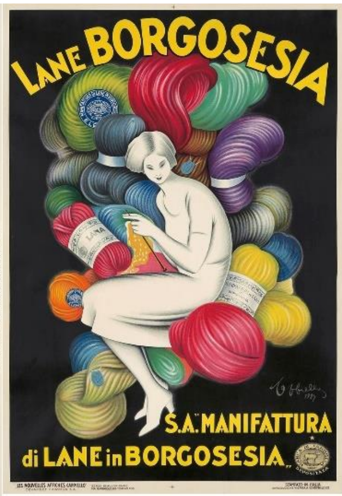


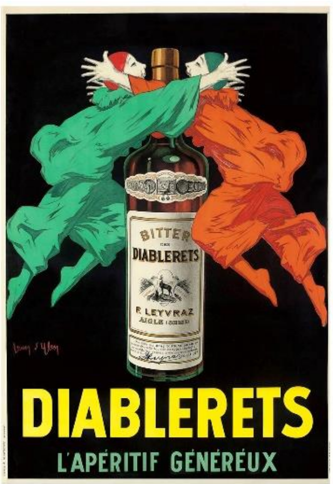
Fig. 23. Jean d'Ylen, Fiorino Asti Spumante, 1922; Fig. 24. Leonetto Cappiello, Bitter Campari, 1921; Fig. 25. Jean d'Ylen, Teinture Idéale, 1928; Fig. 26. Leonetto Cappiello, Lane Borgosesia, 1927.

In the posters for the Longines (1927) and Zenit (1928) watches, the subject is the same, Kronos the inexorable lord of time, a winged older man, whom Cappiello depicts in an intense yellow that stands out against a background of black and ultramarine blue and reproduced by d'Ylen with a scarlet red body standing out against the dark background. Instead, an environment shaded from black to green is found in the advertising for Barbier Dauphin (1937) by Cappiello and for Filver (1926) by d'Ylen.

The latter, for Fiorino Asti Spumante (1922), presents, against a black background, a figure of a dancer in action, dressed in predominantly eighteenth-century fashion yellow, from the wig to the shoes, and who seems almost to be dancing, holding at arm's length an oversized bottle of sparkling wine, about the size of himself. Two graphic details suggest the nearly human personification of the bottle: the features of a female face with eyes, nose and mouth can be sensed in the ochre to gold colour patterns of the cork that covers the neck of the bottle; then in the dazzling white foam that gushes from the newly uncorked bottle and gathers in shape like the white wigs of eighteenth-century ladies.

One of Leonetto Cappiello's most iconic posters is the one for Bitter Campari (1921), printed by Devambez: a dynamic and brilliant figure floating on a black background. The clown, or a little spirit, emerges from the peeled orange peel in a spiral with Campari in his hand. The character dressed in a tight red polka-dotted jumpsuit echoes the carmine colour of the drink.

Jean d'Ylen uses a similar colour scheme for Teinture Idéale (1928), where a white maiden dances amidst a swirl of small spherical lanterns of multicoloured lights, and by Cappiello for Lane Borgosesia (1927), where a girl dyed white knits surrounded by balls of colourful wool.



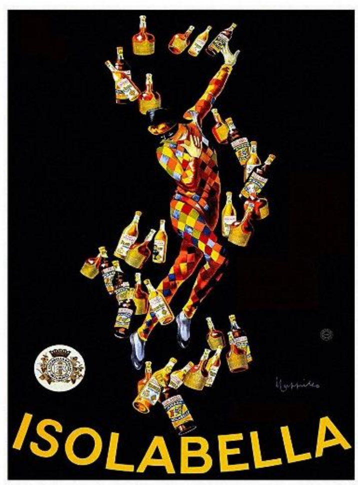


Fig. 27. Jean d'Ylen, Diablerets, 1928; Fig. 28. Leonetto Cappiello, Asti Robba, 1921; Fig. 29. Jean d'Ylen, Porto Constantino, 1928; Fig. 30. Leonetto Cappiello, Isolabella, 1912.

In the poster for Diablerets (c. 1928), Jean d'Ylen draws two embracing pierrots dressed in green and red on a black background, depicting full-length and dynamic movement as if dancing.

The author employs the effects of depth and harmony due to the juxtaposition of complementary colours; the bottle also exploits the same colour codes obtained from the green and red shades, further emphasised by the white labelling. In the poster for Asti Robba (1921), Cappiello also depicts two dancing pierrots holding a cup of the product in unison, touching the container with their lips, and almost kissing it in a decidedly delicate and sensual pose.

There is no direct mention of Italy, but the product's designation of origin is given by choice of emblematic national colours: white for the pierrot's dress, green and red for the lettering.

In the advertisement for Porto Constantino (1928), Jean d'Ylen invents a clownish character dressed elegantly in white, which raises the bottle of the product to the sky in a pose almost as if it was a coveted trophy and engages in an acrobatic dance, remaining for a moment suspended in space against the black background.

Worthy of note is the characterisation of the staggered shadows, in dark green and red, as if generated by two different light sources. In the poster for Isolabella (1910), Cappiello presents us with a graceful polychrome harlequin with tawny hair, dancing among a whirlwind of bottles of liqueurs made by the Milanese company Isolabella; the drawn spiral of products with colourful labels is ideally connected to the central figure's colourful lozenge costume, drawing the viewer's attention.

Fig. 31. A street in Paris, with posters by Jean d'Ylen and Leonetto Cappiello, c. 1930.

6. Conclusions

In the bibliographies and biographies on the two artists, almost nothing is found about Jean D'Ylen, we have no information on their professional relationships at the time of their employment at Vercasson.

Severo Pozzati, a.k.a. Sepo, a well-known French-Italian advertising poster artist, recounts: 'Vercasson had two painters of very little value on staff, in addition to Cappiello: Jean D'Ylen and an Englishman specialising in portraits of children (...). During the war, Cappiello left the company for political reasons (...). Jean d'Ylen took Cappiello's place with the task of copying the master's sketches that had remained unsold, as the publisher's low revenge against Cappiello who had abandoned him" [7]. This observation by Sepo casts a shadow on Jean D'Ylen's career; indeed, the lack of precise biographical information on the artist is somewhat strange, given the enormous success he enjoyed in France and England.

Despite his production of over three hundred posters, and although recognised by some contemporaries as a master of the modern poster, Jean d'Ylen, unlike Cappiello, was soon forgotten. Within a decade, the characters in his posters would appear exaggerated and anachronistic, eclipsed by the models proposed by the emerging poster artists Cassandre, Paul Colin, Jean Carlù, Charles Loupot, and Sepo, by their posters created in a new, modern, synthetic, essential style.

What is certain is that the two authors share numerous formal and compositional choices. For example, they share the search for dynamism in the characters that animate their posters, figures that always appear in movement, in plastic poses, almost dancing; these are beautiful and graceful maidens in light, fluttering dresses, or funny clowns, white or coloured pierrots, Venetian damsels and noblemen in 18th-century dresses, devils and Mephistophelean characters, exotic animals in imaginative, bright colours. The two Authors adopt almost identical chromatic solutions for the backgrounds, which are usually black or monochromatic, with a prevalence of red, green and blue tones; the choice of fonts is also similar, 'stick', sans serif, usually coloured in yellow or teal, chromatic solutions that guarantee legibility and prominence.

From the little information we have found, we deduce that there was no great collaboration between the two: Cappiello began his experience with the 'Etablissements Vercasson' as early as November 1900, and from 1911 he was 'Maîtres de l'affiche' in a decidedly top position; Jean d'Ylen arrived at Vercasson around 1910, and is described as a collaborator of the already famous master: from this we deduce that he acquired his style and manner of composition from him. Cappiello left Vercasson between 1914 and the following year, leaving the printing house with a large number of sketches and drafts that would most likely be reworked and finished in the following years by Jean d'Ylen; the latter, however, would only become 'Maîtres de l'affiche' for the "Etablissements Vercasson" in 1922, a position he would leave due to disagreements 12 years later in 1934.

The chromatic choices experimented by Cappiello in his posters from the first decade of the 20th century had already proved to be appropriate and adequate to attract the viewer's attention. In the following decades, both the Leghorn master and later Jean d'Ylen would continue to employ identical compositional and chromatic choices in their works that had proven to be highly effective in the communicative language of street posters.

Colour in the posters of Leonetto Cappiello and Jean d'Ylen will never be forgotten; the latter stated in 1921: "A poster must be expressive, colourful and have an attraction that captures the attention of a passer-by".

Cappiello stated in a French radio interview of the 1939: "(...) the poster must above all be a visual experience, an act of authority over the passer-by. A well-designed and well-coloured poster can quickly introduce a new product or revive an old and forgotten one" [8].

7. Conflict of interest declaration

The author states that there are no potential conflicts.

8. Funding source declaration

The author states that no funding was involved.

9. Short biography of the author

Marcello Scalzo - Ph.D. and Associate Professor (Icar/17) at the Department of Architecture - University of the Studi in Florence (Italy), where he teaches in the disciplines of Drawing, Survey, Design, Representation, History of Poster, Graphics and Communication. In the latter fields, he produces publications exploring links and connections between visual arts and video; he has also organised exhibitions, performances and installations in the most important squares in Florence.

Notes

[1] Gallo Max, *I manifesti nella storia e nel costume*, Arnaldo Mondadori Editore, Milan 1976, p. 79.
[2] Le Frou-Frou (New Asnières lithograph), Le Journal (Imprint Charles Verneau, Paris), Les Folies Bergères e Hélène Chauvin (Imprint Chaix,

Ateliers Chéret, Parigi) in**:** AA.VV., *Cappiello 1875-1942,* Edition de la Réunion des Musées Nationaux, Paris 1981, p. 114.
[3] "World War I, which broke out in Europe in 1914, provided Cappiello with a natural break to escape the gruelling contract with Vercasson". (Jack Rennert, *Cappiello. The poster of Leonetto Cappiello*, The Poster Art Library, New York 2004, p. 16).
[4] Jack Rennert, *Cappiello,* 2004, (cit.), p. 16.
[5] AA.VV., *Leonetto Cappiello - L'affiche et la parfumerie*, Editions Faton, Dijon 2020, p. 32.
[6] AA.VV., *Leonetto Cappiello,* 2020, cit., p. 32.
[7] Forni Dante, Forni Romeo, *Sepo - settant'anni con l'arte*, Pendragon, Bologna 2008, p. 79.
[8] Monti Raffaele, Matucci Elisabetta, *Leonetto Cappiello - dalla pittura alla grafica*, Artificio, Florence 1985, p. 104.

Licensing terms

References

Cappiello 1875-1942, (1981). Paris: Edition de la Réunion des Musées Nationaux.

Forni, D. and Forni, R. (2008) *Sepo - settant'anni con l'arte*. Bologna: Pendragon.

Gallo, M. (1976) *I manifesti nella storia e nel costume*. Milano: Mondadori.

Leonetto Cappiello - L'affiche et la parfumerie, (2020). Dijon (Borgogna-Franca Contea): Editions Faton.

Monti, R. and Matucci, E. (1985) *Leonetto Cappiello - dalla pittura alla grafica*. Firenze: Artificio.

Rennert, J. (2004) *Cappiello. The poster of Leonetto Cappiello*. New York: The Poster Art Library.

Viénot, J. (1946) *L. Cappiello, sa vie et son Œuvre*. Paris: Edition de Clermont.

Reflectance hyperspectral imaging for colorimetric and spectroscopic studies: the analysis of an impressionist painting.

Alice Pertica[1], Andrea Casini[1], Costanza Cucci[1], Marcello Picollo[1], Lorenzo Stefani[1], Muriel Vervat[2]

[1] *IFAC-CNR, Via Madonna del Piano 10, 50019 Sesto Fiorentino (FI), Italy*

[2] *Studio Muriel Vervat, Via dei Velluti 29r, 50125 Firenze, Italy*

Corresponding author: Alice Pertica (alicepertica@gmail.com)

ABSTRACT

In the last few years reflectance hyperspectral imaging (HSI) has been increasingly employed in the study of cultural heritage and its conservation. HSI systems acquire hundreds of images in narrow contiguous spectral bands in the visible (400-750 nm) and near infrared (750-2500 nm) spectral regions. These form a tridimensional data set called “cube-file”: the two coordinates x and y are associated to the spatial information, while the third one to the spectral information. By manipulating this cube-file it is possible to obtain different kind of information: reflectance spectra, colorimetric data, and images at different spectral bands (or range).
In particular, this article will focus on the combination of colorimetric and spectroscopic analyses for the study of artworks, with the final aim of highlighting the colorimetric differences between different pigments. To reach this goal, a 19th century easel painting was analyzed with a HSI system developed at the “Nello Carrara” Institute of Applied Physics. Starting from the cube-file, it was possible to extract the reflectance spectra for different areas of color and to calculate the colorimetric values for these pixels. Therefore, the materials were identified, and this allowed to compare the different shades of hues – obtained with different pigments – with their colorimetric values.

KEYWORDS reflectance hyperspectral imaging, spectroscopy, colorimetry, conservation science, easel painting.

RECEIVED 31/03/2023; **REVISED** 30/07/2023; **ACCEPTED** 09/08/2023

1. Introduction

Reflectance hyperspectral imaging (HSI) is a relatively new technique, originally developed for remote sensing and astrophysics (Ming *et al.*, 1993; Nieke *et al*., 1997; Mouroulis *et al*., 1998). Nowadays it is increasingly employed in the field of art conservation science, for the analysis and the documentation of artworks. HSI is a non-invasive technique, which consists in the acquisition of hundreds of images in spectral bands that are narrow and contiguous, usually with a bandwidth less than 10 nm. These bands can belong to the visible (Vis 400-750 nm) and/or near infrared (NIR 750-2500 nm) spectral regions [1] (Verhoeven, 2018). These images together form a tridimensional data set known as "cube-file", in which the two coordinates x and y represent the spatial information, while the third dimension contains the spectral information (λ, wavelength). By manipulating these cube-files it is possible to obtain several different kinds of information. Firstly, it is possible to extract images at different wavelengths for every spectral band (or range): it permits to detect potential underdrawings, restorations, *pentimenti*, damages and other hidden details. Secondly, the extraction of a reflectance spectrum for each pixel of the image allows – potentially – identifying the pigments and other materials employed by the artists (Cucci, *et al.*, 2016; Picollo, *et al.*, 2020; Striova, *et al*., 2020). Moreover, it is possible to calculate the colorimetric values for each pixel, but only if the measurement geometry follows the recommendations given by the International Commission on Illumination (CIE) (CIE, 2004; Picollo *et al.*, 2023). These values are obtained following the calculation procedures that are provided by the CIE (Marcus, 1998; Berns, 2001; Burger & Burge, 2009). Lastly, it is very important to remember that also the application of algorithms could help to find other details or information about the artistic technique (Cucci, *et al.*, 2016; Picollo, *et al.*, 2020; Striova, *et al*., 2020).

In addition, the HSI systems have been employed in the analysis of different works of art, from easel and mural paintings to paper artefacts (Cucci, *et al.*, 2015; Cucci, *et al.*, 2016; Delaney *et al.* 2016; Mounier & Daniel, 2017), artistic glass (Perri, *et al.*, 2019; Palomar, *et al.*, 2019) and photographic films (Picollo, *et al.*, 2020; Cucci, *et al.*, 2023).

Everything considered, it is now evident how hyperspectral imaging is a very versatile instrument for the non-invasive investigation and documentation of different kinds, mainly 2D, of cultural heritage objects.

In this paper, the focus will be the combination of reflectance spectroscopy and colorimetry. They are two non-invasive techniques that are often employed in the analysis of artworks (Bacci, 2000; De la Roja, *et al*., 2007; Lorusso, *et al*., 2007; Gil, *et al*., 2014). With hyperspectral imaging these methodologies can be carried out by using just one instrument. Therefore, one of the aims of this work is to demonstrate the versatility and the usefulness of this instrument to study the hues of color and the used materials. The hyperspectral system employed to reach this goal is the one designed and developed at the "Nello Carrara" Institute of Applied Physics (Florence, Italy). Specifically, it was used to analyze a 19th century painting: the final aim is in fact to highlight the colorimetric difference between different pigments of the same color, by comparing and connecting the materials to the shades of hue.

2. Method

2.1. *Case study*

The 19th century easel painting (24.5×32.6 cm, private collection) represents a floral composition, with roses, probably peonies and a wood log (Fig. 1). It dates back to the impressionist period and it has the signature – on the bottom left corner – of the famous painter Édouard Manet (Paris, 1832-1883).

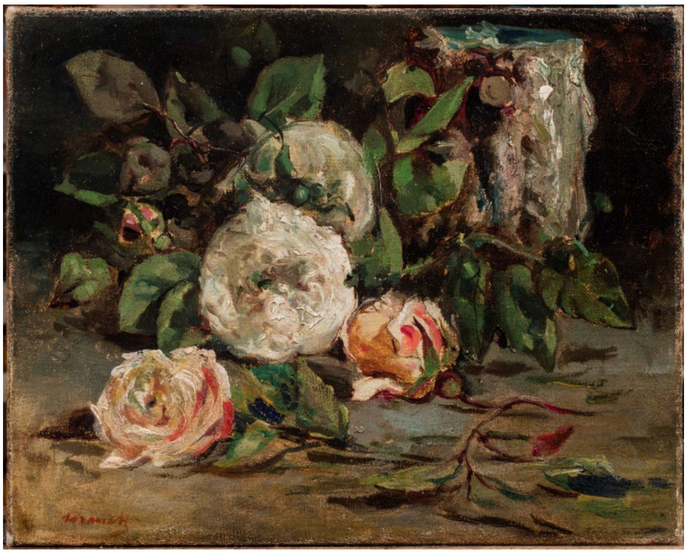


Fig. 1. The analyzed painting

Starting from the acquired cube-files, it was possible to obtain the reflectance spectra for selected pixels of the image – chosen among the different areas of color – to tentatively identify the pigments that composed the artist's color palette. Instead, the values of the colorimetric coordinates for the same pixels were calculated in the CIE L*a*b* 1976 color space (Burger & Burge, 2009). Subsequently, these data were compared among them to find the colorimetric difference between different pigments.

2.2. *Experimental*

The hyperspectral system employed in this study was designed and developed at IFAC-CNR. It is composed of two hyperspectral heads that are alternatively mounted on a moving mechanical structure (for pushbroom scanning). One head works between 400 and 900 nm (visible and near-infrared, VNIR), with a telecentric objective (Opto-Engineering Srl) and a prism-grating-prism (PGP) line-spectrograph (Specim ImSpector™ mod. V10E) connected with a digital CCD camera (Hamamatsu CCD ORCA-ERG) (Cucci, *et al.*, 2011). The other head operates between 950 and 1650 nm (short-wave infrared, SWIR), with a telecentric objective, a PGP line spectrograph (Specim ImSpector™ mod. N17E) and a digital camera with an InGaAs array (Xenics® mod. Xeva 1.7-640) (Cucci, *et al.*, 2013).

The illumination module consists in two fiber optics illuminators which are fixed to the scan-head so as they light the artwork with an angle of 45°. This is essential to obtain a 45°/0° illumination/observation geometry, suitable for colorimetric analyses. The radiation comes from a Quartz Tungsten Halogen lamp (QTH, 150 W, 3200 K) equipped with a thermal filter during visible measurements, replaced with a filter which blocks visible radiation for SWIR measurements.

This instrument has high spatial and spectral resolutions. The spatial sampling is 11.4 points/mm in the VNIR region and 9.2 points/mm in the SWIR setup. The spectral sampling of the VNIR cube is 1.25 nm, with 400 bands and a spectral resolution of 2.5 nm. The second cube, the SWIR one, has a spectral sampling of 2.1 nm, with 332 bands and a spectral resolution of 6 nm. At the end, two cube-files are obtained, with a total of 732 spectral bands from 400 to 1650 nm.

The obtained cube-files were manipulated using ENVI®, a software designed for hyperspectral images processing and analysis. The reflectance spectra were firstly visualized with ENVI®, saved as .txt files in order to process them with Origin 6.0, a graphing and data analysis software.

The colorimetric values were calculated from the reflectance spectra with programs developed specifically for this aim at IFAC (Picollo, *et al.*, 2020; Cherubini, *et al.*, 2023). The colorimetric images – extracted from the hyperspectral ones – contain the L*, a*, b* values for the CIE 1931 2° Standard Observer with illuminant D65, reported as separated floating point TIFF images, which can be displayed and analyzed with image processing programs, in this case they were obtained using Fiji – ImageJ.

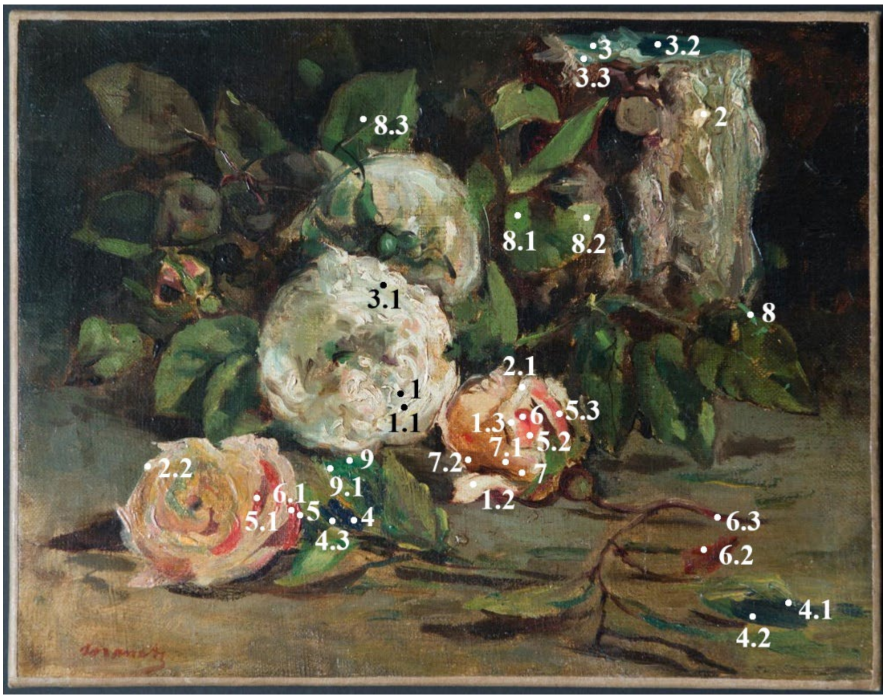


Fig. 2. The points from which the reflectance spectra were extracted.

3. Results

The selected points from which the reflectance spectra were extracted and the colorimetric coordinates calculated are displayed in Fig. 2. The first ones were obtained from the cubes (from an area of 5×5 pixels [2], 0.44×0.44 mm for the VNIR cube) and analyzed to identify the materials by using the SABeC IFAC-CNR Spectral Database (https://spectradb.ifac.cnr.it) and references from the literature. Instead, the colorimetric values were reported in the L*a*b* 1976 color space.

In the following paragraphs the results will be presented divided according to the areas of color.

POINT	PIGMENT	L*	a*	b*
1	Lead white	80.82	0.18	21.64
1.1	“	85.44	2.09	18.53
1.2	“	76.61	-1.21	30.17
1.3	“	69.64	5.06	23.66
2	Lithopone	74.23	2.79	27.05
2.1	“	73.83	3.58	27.30
2.2	“	74.05	-0.31	19.23

*Table 1. CIE L*a*b* 1976 values for each point of the white areas and their pigment attribution.*

3.1. *White areas*

The white pigment mostly employed by the artist is lead white (basic lead carbonate $(PbCO_3)_2 \cdot Pb(OH)_2$), but there are some areas – some brushstrokes and the flower in the left corner – that are made with lithopone (mixture of barium sulfate, $BaSO_4$, and zinc sulfide, ZnS).
The first one was identified thanks to the absorption band at 1445 nm (first OH stretching overtone) visible in the SWIR spectrum. Instead, lithopone shows absorption bands at 650 nm and 730 nm, due to the presence of cobalt ions as substituents of the sulfur ion in the zinc sulfide (Fig. 3). This type of lithopone belongs to the improved version of pigment developed in the 1920s (Bacci, et al., 2007): this and the fact that this pigment is used only in restricted areas might be attributable to following retouching.

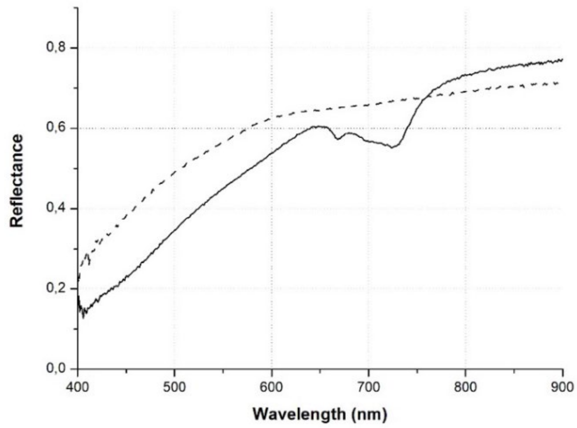


Fig. 3. Reflectance spectra of lithopone (solid line, point 2) and lead white (dash line, point 1) (AVG 5×5).

From a colorimetric point of view (Table 1), both pigments have a high value of L*, since they are white pigments with a high brightness. However, lithopone has higher a* and b* values (more red and yellow components) than lead white, resulting in a warmer hue. This yellowing effect is evident even to the naked eye and might be due to a differentiated aging than other white zones.

3.2. *Blue areas*

The blue areas are made with two different pigments: in the upper part of the painting the artist employed Prussian blue (ferric ferrocyanide, $Fe_4[Fe(CN)_6]_3$), while in the lower part some zones are obtained with the ultramarine blue (lapis lazuli, $Na_{8-10}Al_6Si_6O_{24}S_{2-4}$).
The reflectance spectrum of Prussian blue shows an absorption band at 730 nm, whereas ultramarine has an absorption band at 600 nm and both transitions are due to charge-transfer processes (Fig. 4) (Bacci, 2000; Aceto, *et al.*, 2014).

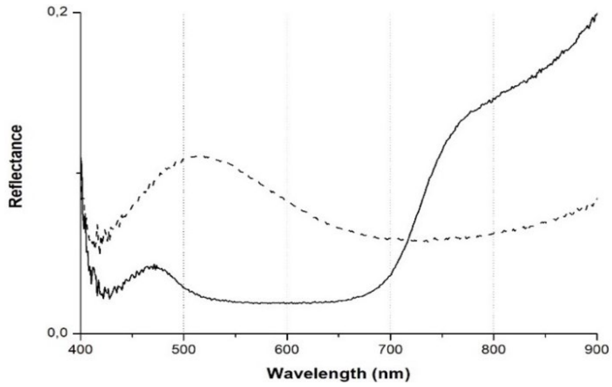


Fig. 4. Reflectance spectra of ultramarine blue (solid line, point 4) and Prussian blue (dash line, point 3) (AVG 5×5).

Since the artist used ultramarine blue to depict some shadows, the resulting color is quite dark, with low values of L*. On the contrary, Prussian blue was employed to obtain different shades of blue, from the brightest in the central flower to the darkest in the wooden log. For example, point 3.1 is a very light blue, while point 3.2 is darker, with L* values similar to ultramarine. In general, this pigment has more green and yellow components than ultramarine blue, in fact every point has a positive value of b*, that is far from the usual values of a blue pigment. For instance, point 3 shows a more greenish hue, also evident from the value of a* (Table 2).

POINT	PIGMENT	L*	a*	b*
3	Prussian blue	32.51	-17.07	7.97
3.1	“	57.63	-5.94	9.82
3.2	“	18.21	-7.61	1.32
3.3	“	35.95	-9.90	4.29
4	Ultramarine blue	10.28	-2.31	-9.20
4.1	“	24.22	-3.54	-1.86
4.2	“	18.44	-3.60	2.72
4.3	“	15.15	-3.78	-0.31

*Table 2. CIE L*a*b* 1976 values for each point of the blue areas and their pigment attribution.*

3.3. *Red areas*

To obtain shades of red the artist used vermilion (mercury sulfide, HgS) and a red lake. The first one shows a typical sigmoid-shaped spectrum with an inflection point at around 600 nm due to band-to-band transition. The red lake shows a similar sigmoidal trend, although with a less steep rise after the inflection point (Fig. 5). It was not possible to define its origin (vegetal or animal) because the typical absorption bands in the 500-580 nm range are not visible (Aceto, *et al*., 2014; Vitorino, *et al*., 2015).

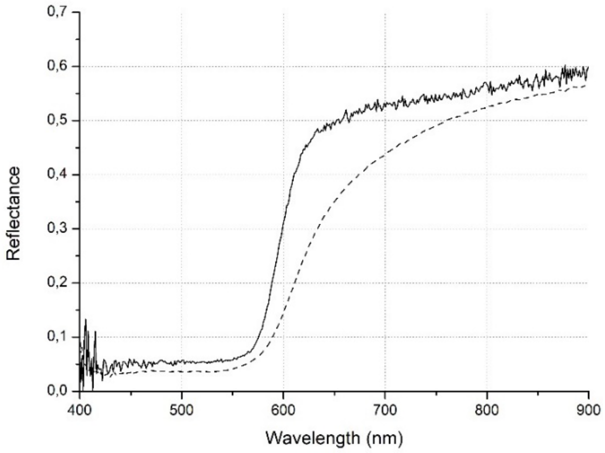


Fig. 5. Reflectance spectra of vermilion (solid line, point 5) and red lake (dash line, point 6) (AVG 5×5).

Colorimetric data (Table 3) show that the areas painted with vermilion seem to be more vivid than the one with the red lake (higher L* values). In general, it has a colder hue, because of the lower b* values. Nevertheless, there are still some areas that show different shades, such as point 5.2 (vermilion) that has a higher component of yellow compared to the other points. For what concerns the red lake, instead, point 6.2 has a higher value of b* than the other points, while 6.3 has a very low value of this coordinate, which means a less yellow component. This can be due to the influence of a darker pigment below the lake in this area.

POINT	PIGMENT	L*	a*	b*
5	Vermilion	41.90	39.25	19.52
5.1	"	36.10	33.63	19.59
5.2	"	48.31	36.57	31.00
5.3	"	44.39	35.64	23.17
6	Red lake	29.77	38.50	26.43
6.1	"	31.89	38.77	28.09
6.2	"	28.98	40.55	40.72
6.3	"	24.23	29.68	14.80

*Table 3. CIE L*a*b* 1976 values for each point of the red areas and their pigment attribution.*

3.4. *Brown areas*

An iron oxide pigment (Fe_2O_3) was used to create brownish areas and shadows. This pigment is identifiable from the absorption band in the reflectance spectra at 550 nm caused by charge-transfer transitions, the shoulder at 680 nm and the band at 850 nm, both due to ligand field transitions (Fig. 6) (Aceto, et al., 2014).
Since it is a brown pigment, it shows high values of red and yellow components (respectively a* and b*) (Table 4).

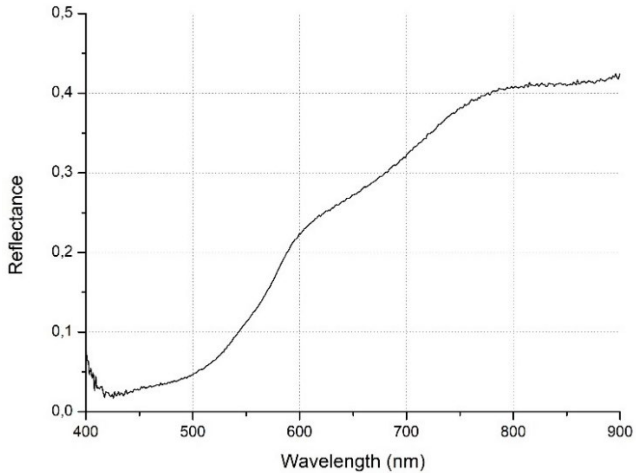


Fig. 6. Reflectance spectra of iron oxide pigment (point 7) (AVG 5×5).

POINT	PIGMENT	L*	a*	b*
7	Iron oxide pigment	39.18	21.67	37.65
7.1	"	41.54	24.75	38.22
7.2	"	27.93	19.33	26.06

*Table 4. CIE L*a*b* 1976 values for each point of the brown areas and their pigment attribution.*

3.5. *Green areas*

The green pigment that is employed in almost the entire painting is a mixture of Prussian blue and a yellow pigment (that could be chrome yellow – lead chromate – $PbCrO_4$). Nevertheless, there are some leaves in the bottom left part of the painting that are obtained with another green pigment. In fact, this one shows a different reflectance spectrum (Fig. 7), but it was not possible to identify it, even though it may be a chromium-based pigment, according to the shape of the spectrum between 450 and 800 nm. The mixture has higher values of L* than the other green pigment, except for point 8.3 that refers to a darker area, with lower values of a* and b*, which translates to a minor presence of green and yellow in the color. Moreover, the unidentified green shows lower b* values which means that this pigment results colder than the mixture of Prussian blue and yellow.

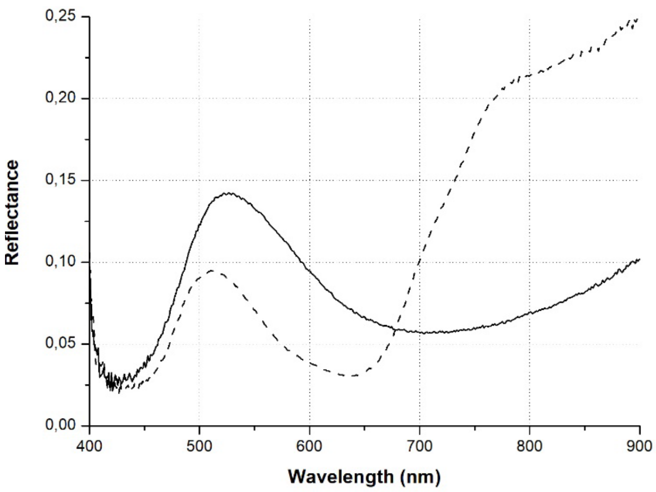


Fig. 7. Reflectance spectra of mixture of Prussian blue and yellow (solid line, point 8) and unidentified green pigment (dash line, point 9) (AVG 5×5).

POINT	PIGMENT	L*	a*	b*
8	Prussian blue + yellow	40.65	-20.83	24.12
8.1	"	37.25	-18.14	26.86
8.2	"	49.31	-6.33	21.77
8.3	"	27.67	-6.46	10.78
9	Unidentified green	32.83	-24.43	15.84
9.1	"	32.51	-29.61	16.16

*Table 5. CIE L*a*b* 1976 values for each point of the green areas and their pigment attribution*

4. Conclusion

This study – among the others – shows how HSI is a very useful tool in the study of artworks and their materials. In this case, it was possible to obtain the colorimetric data and the reflectance information by manipulating the hyperspectral cube-files (Picollo, *et al.*, 2020; Cherubini, *et al.*, 2023). The combination between them allowed to highlight and understand the differences in the tones between different pigments used to create the same color. To summarize, in the whites the presence of lithopone is evident – apart from their reflectance spectra – from the more yellow hue than the lead white that can be imputed to following retouching. In blue areas, ultramarine blue is used almost pure to realize very dark shadows, while Prussian blue is employed with different shades, but in general with a greener hue. The red details are created with vermilion and the glazes with a red lake; the first one it is more vivid and cold than the second one. On the other hand, brown shadows and areas are obtained with an iron oxide pigment which shows higher values of red and yellow in its colorimetric coordinates. The green hues are depicted by using a mixture of Prussian blue and yellow and probably a chromium-based pigment: the first one is used with different shades, while the second is used only in a restricted area of the painting and appears colder than the mixture.

In conclusion, HSI is very powerful non-invasive technique that can potentially provide various information about the works of art, the materials of which they are made of and their artistic production technique.

5. Conflict of interest declaration

The authors state that no actual or potential conflict of interest exist with other people or organizations.

6. Funding source declaration

The authors state that no external funding has been involved in this study.

7. Short biography of the authors

Alice Pertica - graduated in Science and materials for conservation and restoration of cultural heritage at the University of Florence. Her interests include non-invasive investigation of cultural heritage.

Andrea Casini - MSc in Physics in 1968, has been a researcher at IFAC-CNR from 1972 to 2010. Expert in signal and image processing, for many years he has been developing imaging spectroscopic methodologies for the study of works of art in the "Integrated spectroscopic methods for the diagnostics and monitoring of cultural and environmental heritage" project, with which he continues to collaborate as associate researcher.

Costanza Cucci - got her Physics "Laurea" and Ph.D. in Conservation Science at the Florence University. Currently she is a researcher at IFAC-CNR. Her research focus is on spectroscopic techniques and data-processing algorithms applied to the fields of cultural heritage, environmental monitoring, and safety food controls.

Marcello Picollo - Ph.D., is a researcher at IFAC-CNR. His interests include color measurement, Vis-NIR Hyperspectral Imaging, and spot size UV-Vis-IR spectroscopic investigations of 2D polychrome objects.

Lorenzo Stefani - is a technician in telecommunications at IFAC-CNR. He is in charge of the development of hardware and software for computer-controlled instrumentation for the non-invasive and in situ study of artworks.

Muriel Vervat - Graduated from the Higher Education School of the Opificio delle Pietre Dure in 1983, she carried out a professional activity in the sector of the restoration of paintings on wood and canvas. She is included in the list of restorers of cultural heritage of the MiBACT.

Notes

[1] This division into spectral ranges is the one used in the spectroscopy field. Instead, in the field of detectors it is slightly different (see section 2.2.).

[2] The resulting spectra are the average of every spectrum of each pixel in this area of 5×5 pixels. In the following paragraphs the term "AVG 5×5" will refer to this average.

References

Aceto, M. *et al*. (2014). 'Characterisation of colourants on illuminated manuscripts by portable fibre optic UV-visible-NIR reflectance spectrophotometry', *Analytical Methods*, 6, pp. 1488-1500. doi: 10.1039/c3ay41904e.

Bacci, M. (2000). 'UV-VIS-NIR, FT-IR, and FORS spectroscopies'. In: E. Ciliberto & G. Spoto, eds. *Modern Analytical Methods in Art and Archaeology*. John Wiley and Sons, Inc., pp. 321-361.

Bacci, M. *et al*. (2007). 'Non-invasive identification of white pigments on 20th-century oil paintings by using fiber optic reflectance spectroscopy', *Journal of the American Institute for Conservation*, 46(1), pp. 27-37. doi: 10.1179/019713607806112413.

Berns, R. S. (2001). 'The Science of Digitizing Paintings for Color-Accurate Image Archives: A Review', *Journal of Imaging Science and Technology*, 45(4), pp. 305−325.

Burger, W. & Burge, M. J. (2009). 'Colorimetric Color Spaces'. In: Mackie, I., Ed., 'Principles of Digital Image Processing', *Undergraduate Topics in Computer Science*, chapter 6, pp. 97-124. doi: 10.1007/978-1-84800-195-4_6.

Cherubini, F. *et al.* (2023). 'Application of a hyperspectral camera for colorimetric measurements on polychrome surfaces in a controlled environment and evaluation of three image processing software for displaying colorimetric data: Pros and cons of the methodology presented', *Color Res Appl.*, 48, pp. 210–221. doi: 10.1002/col.22835

CIE (2004). 'Technical Report. Colorimetry', 3rd Edition, Vienna: Commission International de l'Eclairage (CIE).

Cucci, C. *et al*. (2011). 'Open issues in hyperspectral imaging for diagnostics on paintings: when high spectral and spatial resolution turns into data redundancy', *Optics for Arts, Architecture and Archaeology, SPIE*, 8084(III), pp. 1-10. doi: 10.1117/12.889460.

Cucci, C. *et al.* (2013). 'Extending Hyper-Spectral Imaging from Vis to NIR spectral regions: a novel scanner for the in-depth analysis of polychrome surfaces', *Optics for Art, Architecture and Archaeology, SPIE*, 8790(IV), pp. 1-9. doi: 10.1117/12.2020286.

Cucci, C. *et al.* (2015). 'Hyperspectral remote sensing techniques applied to the non-invasive investigation of mural paintings: a feasibility study carried out on a wall painting by Beato Angelico in Florence', *Optics for Arts, Architecture and Achaeology V*, Proc. of SPIE, 9527, 1-9. doi: 10.1117/12.2184743.

Cucci, C., Delaney, J. K. & Picollo, M. (2016). 'Reflectance Hyperspectral Imaging for Investigation of Works of Art: Old Master Paintings and Illuminated Manuscripts', *Accounts of chemical research*, 49, pp. 2070-2079. doi: 10.1021/acs.accounts.6b00048.

Cucci, C., *et al.* (2023). 'A novel Transmittance Vis-NIR Hyper-Spectral Imaging scanner for analysis of photographic negatives: proof-of-concept for a new tool in photography conservation', *Sensors*, 23(7), 3562. doi: 10.3390/s23073562.

De la Roja, J. M. *et al.* (2007). 'Variations in the Colorimetric Characteristics of Verdigris Pictorial Films Depending on the Process Used to Produce the Pigment and the Type of Binding Agent Used in Applying it', *COLOR research and application*, 32(5), pp. 414-423. doi: 10.1002/col.20311.

Delaney, J. K. *et al.* (2016). 'Visible and infrared imaging spectroscopy of paintings and improved reflectography', *Heritage Science*, 4(3), pp. 1-10. doi: 10.1186/s40494-016-0075-4.

Gil, M. *et al.* (2014). 'Material and Diagnostic Characterization of 17th Century Mural Paintings by Spectra-Colorimetry and SEM-EDS: An Insight Look at José de Escovar Workshop at the CONVENT of Na Sra da Saudacao (Southern Portugal)', *COLOR research and application*, 39(3), pp. 288-306. doi: 10.1002/col.21792.

Lorusso, S., Natali, A. & Matteucci, C. (2007). 'Colorimetry applied to the field of cultural heritage: examples of study cases', *Conservation Science in Cultural Heritage*, 7, pp. 187-220.

Marcus, R. T. (1998), 'The measurement of color'. In: Nassau, K., Ed., 'Color for Science, Art and Technology', Amsterdam: Elsevier, chapter 2, pp. 31-96.

Ming, Z., Goosens, R. & Daels L. (1993). 'Application of Satellite Remote Sensing to Soil and Land Use Mapping in the Rolling Hilly Areas of Nanjing, Eastern China', *EARSeL Advances in Remote Sensing*, 2(3), pp. 34-43.

Mounier, A. & Daniel, F. (2017). 'Pigment & dyes in a collection of medieval illuminations (14th-16th century)', *Color Res Appl.,* 42, pp. 807-822. doi: 10.1002/col.22146.

Mouroulis P. *et al.* (1997). 'Trade Studies in Multi/hyperspectral Imaging Systems Final Report', *NASA Earth Science Technology Office USA.*

Nieke J. *et al.* (1997). 'Imaging spaceborne and airborne sensors systems in the beginning of the next century', *Sensors, Systems, and Next-Generation Satellites,* Proc. of SPIE, 3221, pp. 581-592. doi: 10.1117/12.298124.

Palomar, T. *et al.* (2019). 'Analysis of chromophores in stained-glass windows using Visible Hyperspectral Imaging in-situ', *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 223, 1-9. doi: 10.1016/j.saa.2019.117378.

Perri A. *et al.* (2019). 'Hyperspectral imaging with a TWINS birefringent interferometer', *Optics Express*, 27(11), 15956-15967. doi: 10.1364/OE.27.015956.

Picollo, M., *et al.* (2020). 'Hyper-Spectral Imaging Technique in the Cultural Heritage Field: New Possible Scenarios', *Sensors*, 20, p. 2843. doi: 10.3390/s20102843.

Picollo, M., *et al.* (2023). 'Application of Hyper-Spectral Imaging Technique for Colorimetric Analysis of Paintings', *SCIRES-IT-SCIentific RESearch and Information Technology*, 12(2), 69-76.

Striova, J., Dal Fovo, A. & Fontana, R. (2020). 'Reflectance imaging spectroscopy in heritage science', *La Rivista del Nuovo Cimento*, 43, pp. 515-566. doi: 10.1007/s40766-020-00011-6.

Verhoeven, G. (2018). 'Multispectral and Hyperspectral Imaging', *The Encyclopedia of Archaeological Sciences*, pp. 1-4.

Vitorino, T. *et al*. (2015). 'Non-invasive identification of traditional red lake pigments in fourteenth to sixteenth centuries paintings through the use of hyperspectral imaging technique', *Applied Physics A-Materials Science Processing*, 121(3), pp. 891-901. doi: 10.1007/s00339-015-9360-4.

Colour and Light for storytelling and storydoing in museum videogames.

Greta Attademo[1]

[1] *Department of Architecture, University of Naples "Federico II", Naples, Italy. greta.attademo@unina.it*

Corresponding author: Greta Attademo (greta.attademo@unina.it)

ABSTRACT

This paper analyses some cultural videogames produced, in recent years, by art and archaeological museums, in order to understand how colour can become a visual tool to support gaming and cultural storytelling. The traditional methodologies of visual language analysis are adapted to the distinctive features of the new medium, as the interactivity and navigability of virtual game spaces. The aim of the research is to investigate colour both as a tool that the game designer uses to structure the narrative and as a visual element that the player interprets to develop the game actions.

KEYWORDS Cultural heritage, narrative colour, interactive colour, educational videogames, cultural games

RECEIVED 07/02/2023; **REVISED** 18/03/2023; **ACCEPTED** 03/07/2023

1. Introduction

The game sector has expanded rapidly in recent years, revealing the great potential of the videogame as an expressive and communicative medium. This has also happened thanks to the interdisciplinary field of Game Studies interested in pursuing two research paths: the anthropological one explores the psycho-pedagogical value of the videogame and its socio-cultural implications; the semiotic one is based on the design of the videogame, investigating the relationships between new forms of communication and visual language (Pecchinenda, 2010). This latter field of study demonstrates how videogames are not only a social phenomenon, but also the convergence point to redefine our relationship with the world of images (Wolf & Perron, 2003). In fact, videogames have a unique property compared to other visual narratives: they are the first medium that combines visual dynamism and an active participatory role. While the spectator observes the characters' dynamics from the outside in other media, the player is at the centre of the story in videogame, influencing the narrative through his actions thanks to the interaction. The new interactive role of the player, and thus the ability "to manipulate the images reproduced on the screen" (Alinovi, 2002, 17), determines new narrative opportunities also for the represented space that is no longer only observable, but also an explorable virtual place. Therefore, traditional narrative is replaced by what Sean Cubitt (2001) calls 'post-narrative spatialisation'. The designers can control the narrative process by distributing information in the game space (Jenkins, 2004), since they cannot predict every action carried out by the player. The player is tasked to interpret a potentially unlimited number of spatial representations and to produce actions and movements in order to reconstruct the story. The image is the first element to be perceived in the videogame (Günzel, 2008) because the visual component is the most pervasive dimension of the gaming experience (De Leo, 2007). Therefore, the elements of the visual language become a true communicative code between designer and player. Starting from these considerations, the research aims to investigate the narrative role of colour in videogames, analysing how it contributes not only to explicit narrative content, but also to transforming it into movements, actions or choices to be taken by the player.

2. Research Methodology

The topic investigated in this research is still little explored by scholars and, consequently, not provided with a rich bibliography for reference. It is therefore helpful to use the traditional methodologies of colour studies and adapt them to analysing the new medium's main features: the narrative component, the emotional and perceptive immersion, the interaction and the playful exploration of virtual space. Torben Grodal describes the videogame as "the medium that is closest to the basic embodied experience of a story" (2002, p.197). Nicolas Esposito also defines the videogame as "a game which we play thanks to an audiovisual apparatus and which can be based on a story" (2005, p.2). The reference bibliography, therefore, is restricted to those texts that deal mainly with the semiotic, psychological and communicative aspects of colour, as these can be related to the videogames' peculiar features. It is important to circumscribe the type of videogames in the analysis to so-called Cultural Games. These are museum-produced videogames that accurately simulate the features of entertainment games. The only difference is that they introduce places and/or cultural assets into their narrative, with the aim of supporting the knowledge of the artworks and the fruition of the museum. This decision is based on the consideration that colour can be investigated starting from its role in the spatial representation, since the narrative component is a crucial element in these videogames. Furthermore, the control of visual and chromatic language cannot be exclusively determined by gaming requirements in museum products as they are related to culturally significant environments. We analyse three Cultural Games in order to examine the different narrative potential of colour in museum videogames: *Past for Future* (2018) by the National Archaeological Museum in Taranto, *The Medici Game* (2019) by the Uffizi Galleries in Florence and *Prisme7* (2020) by the Centre Pompidou in Paris. The three videogames are selected on the basis of common parameters. These are in fact videogames produced by art and archaeological museums for the purpose of telling stories related to the collections and to the museum. It becomes a priority to analyse the museum context in which colour is also a key component in the interpretation and communication of the artwork. The catchment area is also fundamental. The selected games are appropriate for all age groups and can also be used outside the museum; consequently, the colour choices are made in order to be received by the widest audience sphere. The last parameter is the recent year in which the videogames were produced. Today, in fact, museum videogames are abandoning purposes such as excessive realism and hyper-stimulated graphics, since they cannot compete with entertainment games, and are pursuing a simpler style, linked to communicative and expressive capacity rather than technological impact. Therefore, the research methodology adopted involves a qualitative and comparative analysis of videogames, conducted through the combined use of research methods: the activity of playing game products, the reproduction of their full content through gameplay videos, the reading of scientific writings on the matter, as well as the consultation of auxiliary materials such as blogs, websites and online magazines.

3. Emotional colour

Past for Future is the official videogame of the National Archaeological Museum of Taranto - MArTa. The main character of the horizontally scrolling game is William, a young man who embarks on a journey to get out of an emotional impasse in his life. The journey will lead him to discover the treasures of the museum and the Apulian city; in fact, the main purpose of the game is to narrate the beauty of Taranto, using the MArTa as a link between the ancient and the contemporary city. Colour is used by illustrator Tida Kietsungden in the depiction of the game scenarios to recreate suggestions and emotions that the city and the museum are able to offer the visitor. The videogame team has in fact stated that the main intention is to graphically reproduce the combination of light and colour reflected in the city's millenary architectural stratigraphy, given by the relationship between the sun and the two seas on which Taranto stands. It is therefore crucial to analyse colours not so much in their singularity, but rather in their mutual relationship and interaction (Albers, 2013). The colour palettes adopted in the game space, in fact, reflect the state of happiness or sadness of the main character (Fig.1). The videogame starts with a rainy London skyline and a silent, gloomy house in which William is alone. The shaded areas, as well as the dark and dim tones, reflect the sad and depressed soul of the character, distant both geographically and psychologically from the Italian family. In the following scenes, London gives way to Taranto, recreated by modelling some of its most significant places, such as the historic centre, the archaeological areas and the seaport. The representation of the Apulian city accompanies the character's moral and psychological evolution. The warm hues, the bright, saturated colours reflect the tale of a vivid and shining city in which William discovers himself. This analysis highlights the link between environmental colour properties and feelings of joy/sadness, reinforcing previous studies that have shown that images in a virtual environment leading to the perception of joy tend to be brighter, more saturated and with more colours than images of sadness (DeMelo & Gratch, 2009; Geslin, Jégou & Beaudoin, 2015). The player can also make time jumps between ancient Taranto, a flourishing Spartan colony, and the new city, differentiated in the videogame by the colour (Fig.2). In fact, the player identifies contemporary Taranto through its intense and vivid colours, often further accentuated by black contour lines. On the other hand, pastel colours are used in the drawing of ancient Taranto; the shades and soft points of white, similar to pictorial brushstrokes, recall the idea of a past memory. The archaeologic museum is the link between the two cities: the chromatic qualities of the two temporal dimensions intertwine and mingle in the representation of the exhibition spaces. The colour in *Past for Future* aims, therefore, to elicit emotions similar to those the player might experience when exploring the archaeological ruins of Taranto, thus inviting him to physically visit the city and discover its history.

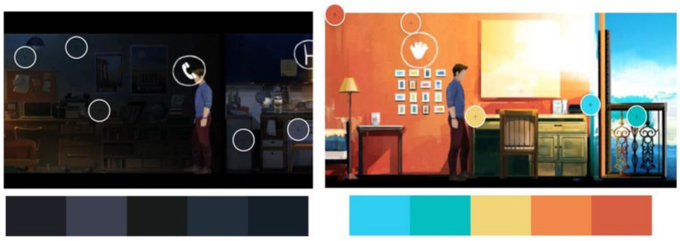


Fig. 1. Colour in Past for Future. The opposing palettes highlight the main character's different emotional states in the cities of London and Taranto.

Fig. 2. Intensity of colour. The differences between contemporary and ancient Taranto are expressed by the contrast between intense and soft colours.

4. Interactive Colour

The Medici Game is the first 3D videogame dedicated to an Italian museum, the Uffizi Galleries in Florence. The game focuses on the famous grand ducal dynasty of the Medici and their sumptuous residence at Palazzo Pitti. The main character of the game is Catherine, a young art historian trapped in the palace at night. She is forced to solve a long series of puzzles that will lead her to discover the palace's secrets, in order to escape the building unharmed. Although the game is set in a virtual reconstruction of the Pitti Palace, the story is mainly focused on the mysteries connected with the Medici family and the artistic masterpieces in its collections. Light and colour assume a crucial role in the narrative as they have the task of creating an atmosphere not existing inside the physical museum spaces, immersing the player in a virtual environment surrounded by mystery and suspense. Colour has always been used to create interest, communicate symbolic messages and trigger emotional responses in visual narratives (D'Andrade & Egan, 1974). In fact, studies show that prolonged exposure to a certain colour can create reactions that connect the viewer to specific symbols and emotions (Gegenfurtner & Sharpe, 2000). This also happens in *The Medici Game*. In particular, the colour black is used to define the tone and atmosphere of the videogame, becoming a symbol of the mystery and darkness that involves and 'imprisons' the player in the adventure. The story in videogames, however, is built through the player's actions and movements, unlike other visual media. The player, in fact, has ample autonomy in the navigation and exploration of the space in *The Medici Game*, being free to move his avatar through the apparently empty and silent rooms of the Pitti Palace. This is convenient from the cultural narrative point of view, as it allows the player to observe all museum environments and artworks in detail. On the other hand, this freedom of movement requires the game designer to be more careful and precise in the representation of virtual environments, as he must attract the player into areas that are crucial for the correct narrative development and for the resolution of puzzles hidden in the space. Colour therefore becomes an useful tool for influencing player's behaviour and choices (Roohi & Forouzandeh, 2019). For this reason, black is often contrasted with other shades of colour in *The Medici Game*: these, although less present, acquire greater visual weight as they focus the player's attention on specific spatial areas. For example, the contrast of black with blue, red or yellow, accentuated by high saturation, indicates to the player the direction in which to move. Also the light-shadow relationship serves to support spatial orientation. The use of colour for wayfinding is certainly a typical property of all videogames, including entertainment games (Stewart, 2017). However, what is particularly interesting is that colour balancing serves to distinguish interactive from non-interactive spatial elements in *The Medici Game*. In fact, it has been proven that colour constitutes an effective code for organising our visual world by grouping similar elements together (Schulz & Sanocki, 2003). This aspect is interesting because the representation of virtual space in a cultural videogame is more complex than that of an entertainment videogame. In this specific case, the spatial model must both be coherent with the physical spaces of the grand ducal palace and allow the development of the story as planned by the game designer. Many cultural assets in gamespace only serve to give completeness to the spatial context, informing the player of their presence and location. Colour allows to highlight interactive artworks (Fig.3) that contain narrative clues functional to the player's investigative story. For example, all the walls are frescoed in the representation of the *Sala di Giovanni da San Giovanni*. This represents a scheme coherent with the physical space of the museum. However, the medallion held by the swan's beak in the south wall fresco stands out because it is depicted in a highly saturated gold colour (Fig.4). This becomes a spatial clue necessary to continue with the game. The colours used are not chosen arbitrarily in *The Medici Game*, but they depend on the Palazzo Pitti's features: the red thus becomes the dominant colour in the Throne Room, the green in the Green Room, the white in the Stucchi Room, and so on.

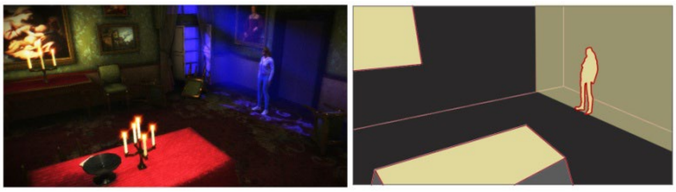


Fig. 3. Colour in The Medici Game. Cultural artifacts that have a narrative function are highlighted by colour.

Fig. 4. The saturation of colour. The highly saturated gold medallion in the Sala di Giovanni da San Giovanni becomes a narrative clue.

5. Thematic Colour

Colour assumes a central role in the story of *Prisme7*, the videogame of the Centre Pompidou in Paris. It becomes a visual and interactive guide capable of transforming even very complex artistic concepts into a stimulating gaming experience. *Prisme7* is a platform game composed of seven levels in which the player is called to move an abstract entity inside different virtual environments. The player is introduced to the world of contemporary art without didactic or informative content, but by immersing himself in specific visual worlds in which colour takes on different features and qualities. They take their inspiration from the poetics of the most famous modern artists from Europe and overseas, such as Xavier Veilhan, Piet Mondrian and Andy Warhol. The exploration of the seven virtual spaces allows the player to investigate seven topics related to colour, namely: functional colour, systemic colour, colour and activism, emotional colour, spiritual colour, light and physics, light and immersion. A specific space has been designed for each topic and a new one can be unlocked only after completing the previous level. The colour functions as a visual interpretive code (Fig.5) (Schulz & Sanocki, 2003); this choice is appropriate not only for the gameplay, but also for the cultural storytelling, because it allows the game designer to break down a complex topic into smaller thematic chapters. The knowledge of art becomes more complex as the game progresses: it starts from the most basic link between colour and function to arrive at the topic of colour as an autonomous and free form of expression in the final level. The first level introduces the player to the topic of functional colour, representing a clear reference to the architectural logic of the Centre Pompidou. The image of the French museum centre is well-known for its exposed systems, whose pipes are differentiated by colour according to their use: yellow for electricity, red for lifts and escalators, green for the water system and blue for ventilation. These elements can also be found in the first virtual game environment (Fig. 6), that is represented as an open space divided by walls on which the artworks are placed and fitted with a system of large coloured tubes. Each spatial element is defined by a specific colour: blue pipes allow the player to move horizontally from one room to another, artwork protection devices are yellow and must not be touched by the player, red platforms send warnings and messages. The player also has to assign a colour to elements that are colourless in this level; by transforming the spatial configuration, he gradually understands that all objects with a specific function will have the same colour.

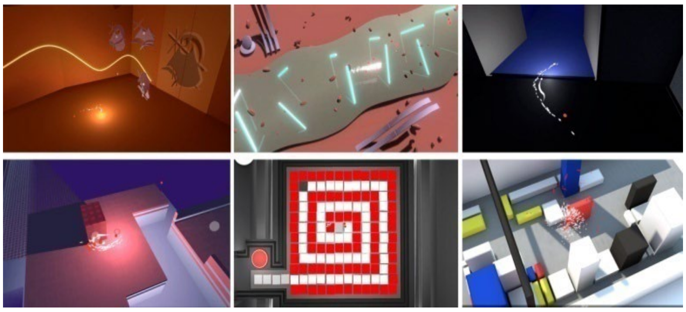


Fig. 5. Colour in Prisme7. Colour guides the player in the construction of artistic concepts.

Fig. 6. Functional colour. Colour in the first level of the game is an allusion to the chromatic logic of the Centre Pompidou in Paris.

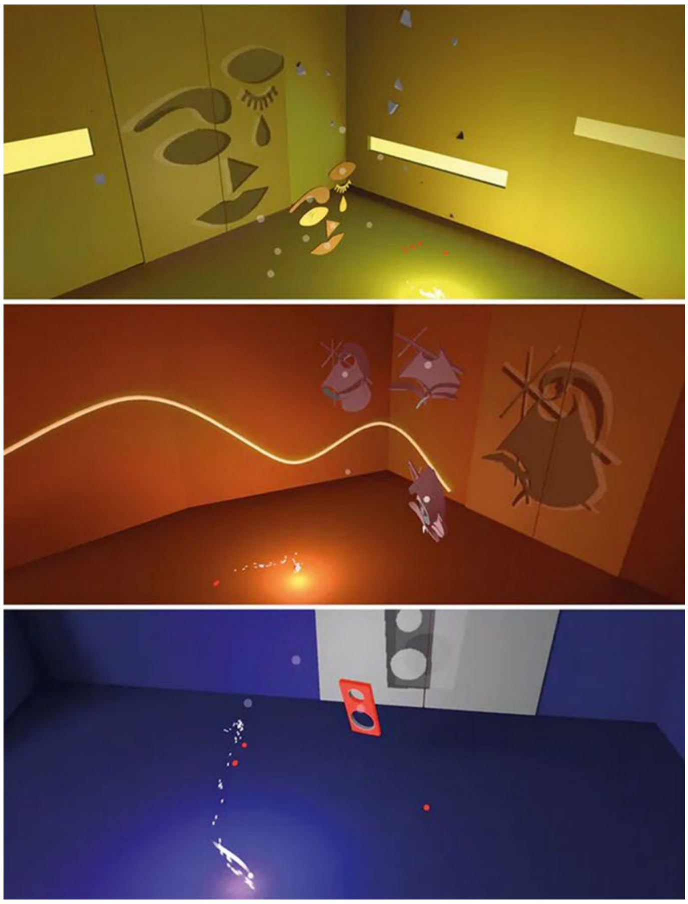


Fig. 7. Colour and light in Prisme7. The topics of colour and light are linked in the last two levels of the game.

Levels 2 to 5 are each inspired by a specific contemporary artist. The second level is deeply influenced by Vera Molnár's artworks, in particular by the painting *Identiques mais différents*; this is in fact one of the prizes to be collected during the game. Colour is used as an algorithmic code that defines a strongly geometric and modular space. The player moves around colouring the floor tiles red, but this produces opposite effects on other tiles, which become white and cannot be walked on. He will have to find the way out by using the logic of colour symmetry and balance. The third level, on the other hand, is inspired by Piet Mondrian's artworks and his idea of art as a social balance activator. The starting space is composed of coloured blocks on a white background, recalling the painting *Composition in Yellow, Red and Blue*. The virtual environment is then transformed into an industrial space where colour activates conveyor belts and unlocks access doors. The fourth chapter pays homage to Picasso, telling about the emotion subjectively communicated by art. Space is thus presented as a blank canvas that starts to be coloured when the player moves to specific points. The spatial image is gradually modelled, leaving the player free to explore and move without following specific rules. The space is created with brushstroke-like movements that symbolise the player's emotion. He himself becomes the creator of the space and artist of the artwork. The fifth level is inspired by Vassily Kandinsky and his mysticism: each spatial area is characterised by pure, abstract shapes and must be activated with colour combinations transcending the symbolism of shapes and colour codes. The last two levels are related to the topic of colour in combination with light. Light and shadow, which are considered immaterial concepts in the common imagination, become concrete elements through which the space can be structurally and physically modified in this videogame (Fig.7). The player varies his actions and movements according to how colour and space interact with each other, unconsciously learning about the central role that light and colour can play in artwork.

6. Conclusions

The research presented in this paper focuses not so much on the colourimetric properties of the colour stimuli, but rather on their semiotic significance as elements of the communicative language able to become a tool of knowledge and memory for people who experience them (Regier et al., 2005). The analysis of three Cultural Games shows, in fact, different and gradually more complex ways of using colour to support stories related to museums and artistic/archaeological heritage (Table 1). The psychology of colour becomes in *Past for Future* one of the main tools for activating emotional and empathic processes between the protagonist and the game space, which are inevitably reflected in the relationship that the developers hope will arise between the player, the city of Taranto and the MArTa. Colour in *The Medici Game* is interpreted as an effective tool by which to tell intangible stories related to the museum. This case also revealed how the analysis of colour in videogames cannot be limited only to spatial images, but requires considerations concerning movement in space and actions on the objects. In this regard, we investigated the ways in which colour allows the construction of a gameplay appropriate and coherent with the story's cultural content, while ensuring the interactive and immersive properties of the videogame. Colour in *Prisme7* becomes a device able to narrate modern and contemporary art through an interactive narrative method. Colour, in fact, allows the construction of a more immediate model for the interpretation of complex content, which can also be understood by those audiences that are unfamiliar with traditional methods of cultural transmission. The three case studies demonstrated how colour can become a narrative tool thanks to its objective features, such as hue, saturation and brightness, through its psychological aspects and relationships. In conclusion, the research does not intend to be exhaustive on the topic, but invites reflection on how a conscious use of colour in Cultural Games can contribute to the construction of museum stories experienced in an unconventional way.

Cultural Games	Narrative use of colour	Narrative purpose of colour	Narrative features of colour
Past for Future	Emotional Colour	to recreate suggestions and emotions that city and museum are able to offer the visitor.	Chromatic interactions; colour contrasts (dark/light tones, luminous/dim tones, cold/warm tones, pastel/sharp colours).
The Medici Game	Interactive Colour	to reproduce a mysterious atmosphere connected to the De Medici family and Palazzo Pitti's secrets; to attract the player into narrative areas.	Colour balance and visual weight; high colour saturation; interactivity of yellow, red, blue and green; light and shadows.
Prisme7	Thematic Colour	to be a visual interpretive code capable of translating complex artistic topics into playful elements.	relationship of colour with elements of the visual language (light, shadows, shapes, spaces) and with artistic compositional logic (balance, symmetry, rhythm, modularity, harmony).

Table 1. Summary table of the narrative use of colour in Cultural Games.

7. Conflict of interest declaration

The author declares that nothing affected her objectivity or independence and original work. Therefore, no conflict of interest exists.

8. Funding source declaration

This research did not receive any specific grant from funding agencies in the public, commercial, or not-forprofit sectors.

9. Short biography of the author(s)

Greta Attademo -• Ph.D in architecture and Adjunt Professor at University of Naples, Department of Architecture (Diarc). Her fields of research are the relationships between the space and visual culture, and drawing in architecture and design.

Licensing terms

References

Albers, J. (2013) *Interazione del colore. Prefazione di Bruno Munari.* Milano: Il Saggiatore.

Alinovi, F. (2002) ‘Serio videoludere. Spunti per una riflessione sul videogioco’, in Bittanti, M. (eds) *Per una cultura dei videogames. Teorie e prassi del video giocare.* Milano: Edizioni Unicopoli, pp.17-55.

Cubitt, S. (2001) *Simulation & Social Theory.* London: Sage.

D'Andrade, R., and Egan, M. (1974) ‘The colors of emotion’, *American Ethnologist,* 1(1), pp. 49–63. https://doi.org/10.1525/ae.1974.1.1.02a00030

De Leo, D. (2007) ‘La fenomenologia della percezione estetica nel nuovo panorama multimediale’, in Limone, P. (eds) *Nuovi media e formazione*. Roma: Armando editore, pp. 263-283.

DeMelo, C. M., and Gratch, J. (2009) ‘The effect of color on expression of joy and sadness in virtual humans’, in *Proceedings of the 3rd International Conference on Affective Computing and Intelligent Interaction and Workshops (ACII ’09)*, pp. 1–7, IEEE, Amsterdam, The Netherlands, September 2009.

Esposito, N. (2005) ‘A Short and Simple Definition of What a Videogame Is’, in Digital Games Research Association (eds), *DiGRA ‘05 - Proceedings of the 2005 DiGRA International Conference: Changing Views - Worlds in Play*. Vancouver: Digital Games Research Association, pp. 1-7.

Gegenfurtner, K., and Sharpe, L. (2000) *Color vision: From genes to perception*. Cambridge: Cambridge University Press.

Geslin, E., Jégou, L., and Beaudoin, D. (2016) ‘How color properties can be used to elicit emotions in video games’, *International Journal of Computer Games Technology* 1(1), pp. 1-9. http://doi.org/10.1155/2016/5182768

Grodal, T. (2002) ‘Video games and the pleasures of control’, in Zillman, D. and Vordered, P. (eds) *LEA’s communication series. Media entertainment: The psychology of its appeal*. Mahwah, NJ: Lawrence Erlbaum Associates Publishers, pp. 197-213.

Günzel, S. (2008). ‘The Space-Image. Interactivity and Spatiality of Computer Games’, in Günzel, S., Liebe, S. M., and Mersch, M.D. (eds) *Philosophy of Computer Games*. Potsdam: University Press, pp. 170-189.

Jenkins, H. (2004) ‘Game Design as Narrative Architecture’, in Wardrip-Fruin, N., and Harrigan, P. (eds) *First Person: New Media as Story, Performance and Game*, Cambridge, MA: The MIT Press, pp. 118-130.

Joosten, E. *et al.* (2010) ‘Colors and emotions in video games’, *11th International Conference on Intelligent Games and Simulation GAME-ON 2010* (ed. Aladdin Ayesh), pp. 61-65.

Joosten, E. *et al*. (2012) ‘Influencing Player Emotions Using Colors’, *Journal of Intelligent Computing,* 3(2), pp. 76-86.

Pecchinenda, G. (2010) *Videogiochi e cultura della simulazione: La nascita dell’ ‘homo game’*. Roma – Bari: Laterza.

Regier, T. et al. (2005) ‘Focal colors are universal after all’, *Proc. Natl. Acad. Sci. U.S.A.*, 102. Doi: 8386–8391 10.1073/pnas.0503281102

Roohi, S., and Forouzandeh, A. (2019) ‘Regarding color psychology principles in adventure games to enhance the sense of immersion’, *Entertainment Computing* 30, pp. 1-9. https://doi.org/10.1016/j.entcom.2019.100298

Stewart, D. (2017) ‘Color in video games. How to choose a palette’, *Gamasutra*. Available at: https://www.gamasutra.com/blogs/DougStewart/20170411/295806/Color_in_Video_Games_How_to_Choose_a_Palette.php. (Accessed: 6 February 2023).

Schulz M. F., and Sanocki, T. (2003) ‘Time course of perceptual grouping by color’, *Psychol. Sci,.* 14, pp. 26–30. Doi: 10.1111/1467-9280.01414

Wolf, M. J., and Perron, B. (2003) *The Video Game Theory Reader*. London: Routledge.