Color and Colorimetry
Multidisciplinary Contributions

Vol. XVIII A

Edited by Albana Muco and Filippo Cherubini

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Presentation

The Color Conference, organized annually by the Gruppo del Colore – Associazione Italiana Colore, has reached its 18th edition in 2023 and was held at Milan Polytechnic branch of Lecco.

This two-day international event featured three invited speakers – **Andrew Stockman**, **Christopher Bauder**, and **Raimondo Schettini** – and the presentation of 70 papers.

The two volumes published in open access – one with 29 papers in Italian and the other with 34 in English – collect the papers presented on September 15th and 16th and are organized as follows: the chapters are grouped and follow the numbering in ascending order of the topics of the Call for Papers.

Finally, the "Color Award/Premio Colore 2023" was awarded to **Gaetano Pesce**. We would like to extend special thanks to the Color Committee – in the persons of Alice Plutino, Eva Mariasole Angelin and Miguel Ángel Herrero Cortell – for their valuable contribution.

Our gratitude goes to Andrea Siniscalco, *chair* of the Conference, for the great work done and to all those who participated, helped and collaborated in the successful realization of the event.

We hope you have a happy reading.

Albana Muco and Filippo Cherubini
December 2023

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Physiology and psychology of light and colour: evaluation of an experimental approach

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Abstract

The application of light and colour studies for human well-being is a promising field in design. While good lighting practice is a critical factor in promoting safety and well-being in the workplace, the potential benefits of using light and colour to influence mood and physiology are yet to be fully explored. Since the discovery of ipRGCs and their role in regulating the circadian cycle, new possibilities have been presented to designers to create environments and products that promote well-being, better mood and improved performance.

Studying the effects of light and colour on psychology and physiology implies understanding the process of vision and its influence on factors such as circadian regulation and mood. Bridging the gap between psychology and physiology is crucial to harnessing these mechanisms for positive outcomes. This process involves three interconnected brain systems: perception, cognition and emotion. Perception is the fundamental system which extracts hierarchical and increasingly complex information from the neural codes of the stimulus. Cognition integrates this information with prior knowledge to create a meaningful representation of the environment. Emotional evaluation occurs concurrently with cognition and influences preferences and behaviour based on the affective valence of the processed information.

Recent studies have shown that humans' perception of colours is influenced not only by visual factors but also by physiological processes. Although, for example, warm and bright colours such as yellow and red are commonly associated with an "activating" effect, while physiologically activating colours are at the opposite end of the spectrum (blue), how this process occurs at the "perceptual" level is not yet well defined. By exploring the relationship between colour and emotion and its potential effects on physiology, designers can create environments or products suited to specific needs, such as promoting relaxation or increasing concentration and alertness.

In this paper, we will describe the process of evaluating various factors and issues in the creation of a practical experiment for the verification of the possible existence of a predictable correlation between physiology and psychology regarding the perception of light and colour from the various psychological biases that can affect the results to the experimental conditions, to obtain results that can be declined in a real lighting design context.

The potential applications of light and colour studies in design are vast and diverse. Lighting design can create engaging spaces that promote well-being. In product design, colour and lighting can enhance the functionality of luminaires to improve many physiological aspects and the appeal of areas. Combining physiology and psychology in this field may enable the creation of elements that enhance daily life. As we learn more about these topics, the possibilities for tailored design will continue to grow.

Keywords: Light, Colour, Physiology, Psychology, Design.

Introduction

The application of light and colour studies for human well-being is a promising field in design. Good lighting practice is crucial for promoting safety and well-being in the workplace. Still, the potential benefits of using light and colour to influence mood and physiology are yet to be fully explored (Siniscalco, Bortolotti and Rossi, 2022). The discovery of ipRGCs (intrinsically photosensitive retinal ganglion cells) and their role in regulating the circadian cycle has opened up new possibilities for designers to create environments and products that promote well-being, better mood, influence behaviours -purchasing or not- and improved performance (Bortolotti *et al.*, 2022, 2023). In order to understand the effects of light and colour on psychology and physiology, it is essential to comprehend the process of vision and its influence on factors such as circadian regulation and mood (Rossi, 2019). This involves three interconnected brain systems: perception, cognition, and emotion. Perception extracts complex information from the stimulus; cognition integrates it with prior knowledge to create a meaningful representation of the environment, and emotional evaluation influences preferences and behaviour based on the affective valence of the processed information (Morrone, Denti and Spinelli, 2002; Pratte *et al.*, 2013).

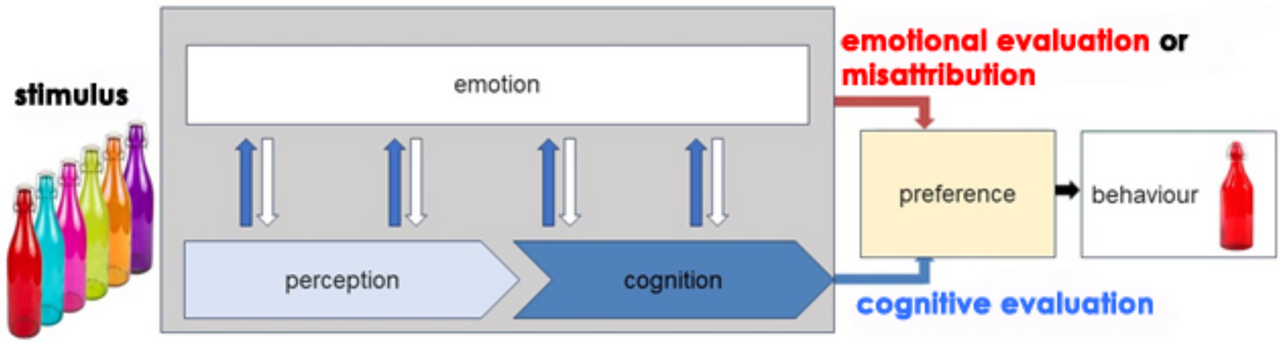

Fig. 1 - Information processing in animal brains (Renoult and Mendelson, 2019)

This perceptual process and the resulting mental representation of colour cannot but depend on light. Light is pivotal in vision and overall well-being, as it synchronises our physiological processes with the natural day-night cycle. Its impact is far-reaching, influencing various physiological and behavioural responses, from hormonal rhythms and the pupillary response to sleep quality, alertness, cognitive performance, and mood (Cajochen, 2007). However, it is essential to note that most of these effects have been studied in controlled laboratory conditions under artificial light, which may limit their general applicability to real-world scenarios. Ideally, studies utilising natural daylight are required, though technical challenges and inherent variability pose a significant obstacle. While the intuitive preference for daylight over artificial light holds, we lack sufficient data to substantiate this claim conclusively. In the present context of 24-hour lit environments, ensuring adequate darkness during the night becomes crucial to prevent circadian phase shifts that can disrupt restorative sleep, a fundamental aspect of maintaining good health. To comprehensively comprehend the effects of light on physiological and psychological processes, we must consider various factors, including the characteristics of the light, the individual's status, personality, living conditions, and cultural influences, along with the intricate interplay of functional brain systems.

Implementing daylight effectively into the spaces of living can be achieved through various means. The development of cutting-edge technologies in the dynamic and online control of lighting products allows designers an ever-increasing level of integration of artificial light with natural light and the process commonly known as “daylight harvesting” (Kandasamy *et al.*, 2018). Encouraging people to spend more time outdoors can be accomplished by providing sheltered outdoor spaces and seating in cities and allowing flexible work schedules that permit regular outdoor breaks during daylight hours. However, successfully integrating these strategies necessitates cultural and climatic awareness, political support, public backing, and education. Additionally, disseminating knowledge about the significant non-visual aspects of daylight is vital. Embracing the challenge of meeting our light needs is a captivating endeavour for society. We are only just beginning to realise the profound importance of daylight for humanity's health and well-being.

Recent studies have revealed that humans' perception of colours is influenced not only by visual factors but also by physiological processes. For example, warm and bright colours like yellow and red are commonly associated with an "activating" effect, but physiologically activating colours are at the opposite end of the spectrum (blue). Understanding how this process occurs at the perceptual level is not yet well-defined (Gao and Xin, 2006; Siniscalco, Bortolotti and Rossi, 2022). By exploring the relationship between colour and emotion and its potential effects on physiology, designers can create environments or products suited to specific needs, such as promoting relaxation or increasing concentration and alertness.

Colour physiology and psychology

What has been said, let us imagine the complex system of "human beings" that has to process a light (or coloured, if you will) stimulus. The perception of these coloured stimuli, we could define them as highly complex stimuli because of their nature composed of different variables in action. Within this intricate study lies a central challenge: the complex nature of the human perception process. We will attempt to explain and break out of this labyrinthine terrain to unravel the intricate workings of how colour stimuli interact with the human psyche. Colour perception and its emotional impact are multifaceted and influenced by many variables, including cultural background, personal experiences and physiological responses (Elliot and Maier, 2012).

This work seeks to shed light on the intricate web of factors that contribute to our emotional reactions to colours. As part of this research, we aim to define and understand the complex stimuli presented by colour in the context of human perception. These stimuli are inherently intricate because of their composition of several interacting variables, making understanding their emotional impact a formidable challenge.

The primary goal of this paper is to clarify the intricate process of evaluating the multitude of factors and complexities involved in conducting a pragmatic experiment to study the connection between colour and emotion. They will meticulously examine the impact of psychological biases on the results and carefully calibrate the experimental conditions. We intend to produce results that can be easily applied in practical lighting design scenarios and various fields where colour plays a crucial role in evoking emotional responses. One central issue this research addresses is the inherent subjectivity of colour perception and its emotional effects. Colours evoke unique emotions and associations in different individuals, often rooted in cultural, personal and psychological factors. This paper aims to navigate this complexity, seeking to identify patterns and correlations in how various colours influence emotional states in diverse populations. This "emotional" subjectivity of colour perception makes knowledge of variables such as the context or culture of reference of the person perceiving a given colour at a given time of paramount importance. In this regard, different theories have already been examined in reviews of the literature (Bortolotti *et al.*, 2022); the most credited theories regarding colour preference from a psychological perspective only the EVT (Palmer and Schloss, 2010) and the Color in context theory of Elliot and Maier (2012).

The "Ecological Valence Theory" (EVT) seeks to show the importance of colour preferences in various aspects of human life, such as buying cars, choosing clothes, decorating the home and designing websites. Although previous studies have described colour preferences from a psychophysical perspective, they have not explained why people have these preferences or like specific colours. The EVT argues that human colour preferences are adaptive in that people are more likely to thrive and reproduce if they are attracted to colours associated with advantageous objects and repelled by those related to disadvantageous objects. EVT combines genetic and learned components: individuals develop colour preferences based on their affective responses to coloured objects throughout their lives. The theory is being tested to determine its ability to explain average colour preferences among individuals for a wide range of colours. The EVT suggests that people should be attracted to colours associated with objects that generally evoke positive emotions and repelled by colours associated with objects that evoke negative emotions. This prediction is compared with other theories, including the cone-opposite contrast model, color appearance theory and color-emotion theory. This theory is most applicable to design and our vision of well-being.

On the other hand, the colour in context theory (Elliot and Maier, 2012) already discussed the shortcomings in the current state of research on colour and its impact on psychological functioning. It emphasises the need for a more rigorous and standardised approach to studying the relationship between colour and psychology. The theory highlights three main weaknesses: **Lack of Proper Color Control**: Many studies do not adequately control colour properties, often only addressing them at device level rather than the spectral level. This lack of control can lead to interpretational ambiguity and undermine the scientific validity of the findings. Proper colour control, although challenging, is deemed essential for rigorous scientific work in this field. **Neglect of Environmental Factors**: Color perception is influenced by various environmental factors such as viewing distance, lighting conditions, and the presence of other colours. Basic colour science research carefully accounts for these factors, but psychological research often ignores them. The theory argues for incorporating rigorous standardisation procedures used in basic colour science research to enhance the quality of psychological studies. **Underpowered Samples**: Many studies in this area suffer from small sample sizes, which can lead to overestimated effect sizes and premature conclusions. The theory stresses the importance of using large, fully powered samples to ensure robust and reliable scientific results. It also encourages adopting best practices from the "evidentiary value movement," such as public archiving of research materials and data, differentiating between exploratory and confirmatory analyses, and preregistering research protocols and studies. In summary, this theory calls for a more meticulous and standardised approach to researching the connection between colour and psychological functioning, addressing issues related to colour control, environmental factors, and sample sizes. It emphasises the importance of adhering to current technological limitations while striving for precise and efficient colour management in research.

These two pieces of research alone would be enough to explain, from our point of view, the problems related to a proper investigation of the study of colour or light on psychological well-being related to colour perception. Still, we will try to explain everything in detail.

Evidence-related issues

Starting from the limitations listed above, also examined in Elliot's study, i.e., lack of proper colour control, in this case, different studies and literature reviews (Bortolotti *et al.*, 2022) have highlighted the issue in this methodological problem would cause all the errors made regarding not only the correct description of the stimulus, but, also the whole experimental part related to the correct presentation of the coloured stimulus (think of a fixed distance from a point x at 0.5 m from a screen and the same stimulus presented at a distance of 1.5 m) the colour perception is also affected by these distances, or the resolution of a pc screen, etc. In many studies in this field, the precautions taken are not meticulously described. These limitations, also indicated in the study mentioned above, relate to the other issues shown by Elliot, i.e. neglect of environmental factors; this, in particular, also concerns the contamination of the survey colour, often not "administered" correctly. The last point shown by Elliot is the underpowered samples; in this case, the sample size is the component that affects the data most of all. To these limitations, however, we must add others; this paragraph addresses the multifaceted challenges associated with chromatic perception testing. It spans various aspects, from the development and design of tests to ethical considerations. The complexities and intricacies within this domain necessitate a comprehensive examination of these issues.

Developing precise tests for chromatic perception is a pivotal step that requires a comprehensive understanding of various intricate factors. The interplay of these factors, including colour sample selection, representation methods, presentation techniques, and the formulation of explicit test objectives, plays a crucial role in determining the efficacy of the resulting tests. Failing to navigate these complexities can have profound implications for the reliability and validity of the outcomes.

Standardization: Achieving test standardization is pivotal to ensure consistent and comparable measurements across individuals and diverse populations. However, standardization can be challenging, especially when accounting for cultural variations in colour perception.

Validation and Norms: To ascertain the validity of a chromatic perception test, validation studies must demonstrate that the test effectively measures its intended construct. Furthermore, establishing norms for result interpretation, often based on reference population samples, is crucial.

Cultural Sensitivity: Color perception can exhibit substantial variation across different cultures. Thus, chromatic perception tests must be sensitive to these cultural differences to prevent cultural bias from infiltrating the results.

Ongoing Assessment: Given that colour perception can change with age or due to ocular pathologies, continuous assessment should be integrated into tests to monitor potential variations over time.

Bias Prevention Education: Test administrators must receive adequate training to prevent the introduction of bias during test administration and result interpretation. Knowledge of potential sources of error is imperative.

Practical Applications: Ultimately, the results of chromatic perception tests find applications in various practical domains, such as product design, art, medicine, and more. Considerations about the practical implementation of these results should be carefully examined.

The problem of classifying colour-emotion associations: The conceptual metaphor theory (Lakoff and Johnson, 1980) can explain the association between colour and emotion. According to this theory, humans apply the structures of other concrete concepts to the target abstract concepts to understand abstract concepts related to thought and action. Therefore, concepts related to emotions, which lack clear boundaries, are understood using colour concepts as scaffolding, as colours are clear perceptual experiences (Sowa, 1999; Williams, Huang and Bargh, 2009). In other words, the metaphorical structures of concepts like "sadness is blue" and "anger is red" facilitate the comprehension of emotion-related concepts.

To recap, there are numerous challenges associated with chromatic perception testing, encompassing technical aspects of test design and ethical and cultural considerations. Addressing these challenges is imperative for obtaining valid and practical insights into chromatic perception.

Conclusions

The number of variables to consider when evaluating human emotions is very high. As mentioned, on some occasions, the psychological response appears to manifest opposite to the typical mechanisms of physiological reaction to light and colour. One plausible hypothesis for why these two paths may appear misaligned is that the physiological response primarily follows non-visual means, which therefore do not involve higher-level processing by the cerebral cortex, while emotions, albeit uncontrolled, result from the brain's visual stimulus processing.

Regarding the physiological response, melanopsin predominates at the retinal level as the stimulus receptor (Provencio et al., 2000). Subsequently, following phototransduction, electric impulses are transmitted through the retina-hypothalamus pathway, processing in the suprachiasmatic nucleus and the response of the pineal gland (controlling melatonin and the circadian rhythm). On the other hand, in response to coloured stimuli, cones operate phototransduction, transmitting impulses through the optic nerve and forming the percept in the posterior cerebral cortex. However, it is demonstrated that cones (visual path) also play a role in synchronizing the circadian cycle (Bhoi *et al.*, 2023). Therefore, it is reasonable to assume that a form of proportionality may exist between the two aspects of the human response to light and colour.

As one can easily imagine, designing a test to assess emotional responses in subjects is a highly complex endeavour. Furthermore, avoiding the pitfalls highlighted by Elliot and Maier entails using a substantial number of subjects and preparing a test setup considering numerous factors. Simply observing a colour on a screen or through a viewer can yield results; however, in practical terms, the emotional response to a simple coloured stimulus may differ from that of the same colour applied, such as ambient lighting in an actual environment. The type of space itself can affect test subjects psychologically. The presence or absence of another person in the test area (an expedient that could also reduce time requirements) can impact the results. The psycho-physical state of the subjects is equally crucial; pre-existing factors such as fatigue, boredom, stress, or excitement can also exert an influence. How many hours did the subject sleep? What is their age, gender, profession, etc.?

If the test were conducted in a potential mock-up of space (rather than using a viewer or monitor), how much would the geometry of the room and the choice of furnishings and objects influence the outcome?

Regarding the choice of colours, it would be possible to illuminate the environment with a single colour at the time to identify subjects' reactions in the most unequivocal manner possible. However, under normal living conditions, it is infrequent to be in environments illuminated monochromatically. The presence of multiple colours can create harmonies or contrasts. The opponent process theory (Ering, 1964), which is observed not only in the visual perception of colours but also in the inhibition of melatonin (Figueiro *et al.*, 2004), suggests that it would be advisable to consider environments that present non-monochromatic visual stimuli as well. When evaluating saturated colours, even if they are "pleasing" according to models like the EVT, what emotional reaction do they provoke in subjects when they alter the perception of everyday objects? For example, think of food chromatically transformed by coloured light: pasta illuminated in purple, fish in yellow, chicken in red, etc.

Considering that several variables impact the time required to conduct the test on each subject, it is clear that it is challenging to address the issues described in the second paragraph.

One approach to addressing the problem could be to start with an initial set of tests using an appropriately calibrated screen or VR headset to present defined colours at a predetermined focal distance. The tests should be open to as many participants as possible, considering variables related to the subjects (age, gender, physical conditions, presence of medical conditions, etc.) and the chromatic stimulus (spectral power distribution, duration, luminous intensity).

Fig. 2 - On the left, an adequately calibrated VR display could deliver coloured light to the test subjects. On the right is a mock-up of a typical living environment illuminated by dynamic coloured lights.

The early assessment of the obtained psychological response will then be cross-referenced with the results of a second series of tests, ideally conducted in a neutral environment rebuilt and illuminated with a dynamic lighting system. In the second series of tests, luminous scenarios known to elicit physiological responses in humans, in terms of activation and stress (Cajochen *et al.*, 2005) as well as relaxation (Noguchi and Sakaguchi, 1999), will be tested using coloured lights and different shades of white light (correlated colour temperature). This procedure will also allow the evaluation of possible proportional relationships between the two mechanisms.

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