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ILLUMINANT METAMERISM ON ARTISTIC PAINTINGS

DOCTORAL DISSERTATION

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METAMERIJA UVJETOVANA PROMJENOM OSVJETLJENJA U SLIKARSTVU

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MENTOR BIOGRAPHY

He graduated from the Faculty of Graphic Arts after completing high school at the Graphic School, specialising in Printing. In 2000, he enrolled in a postgraduate study program at the Faculty of Graphic Arts and became the first Master of Science in Graphic Technology in Croatia in 2002. In January 2005, he obtained his doctorate at the Department of Printing at the Faculty of Graphic Arts with a thesis titled "Optimisation of the Halftone Reproduction System in Printing." Since 1993, he has worked at "Graf" printing house as a director, and later at "AKD" printing house as a production manager and controller of the technological process, eventually becoming the director of the printing house. He participated in the project to produce the new Croatian passport and other secure documents. Before joining the faculty, he worked as a manager for printing systems at Xerox Company. Since 2001, he has been working at the Faculty of Graphic Arts, where he became an assistant professor at the Department of Printing and an associate professor. To date, he has published over 70 scientific and professional papers in Graphic Technology and has participated in numerous international and domestic scientific and professional conferences. He is the author of many chapters published in international scientific books and has contributed to international peer-reviewed journals. In his ten years of industry experience, he completed several courses related to graphic technology and management in Zurich, London, and Budapest. For several years, he has been involved in the work of the scientific-professional Symposium "Blaž Baromić" as a member of the Program and Organisational Committee, as well as a member of the Programme Committee of the Printing and Design Conference. He served as a quality advisor for newspaper printing at the German organisation IFRA and was the project leader for Sincol, which focused on standardising newspaper printing in Croatia and Southeast Europe. He is the President of the Croatian Graphic Arts Society. In 2006, by a decision of the Commercial Court in Zagreb, he became a permanent court expert for the graphic industry and, in 2017, a permanent court expert for the graphic industry, printing, and protection against document and security counterfeiting. He has written textbooks in the field of graphic technology and design, including " Tehničko uređivanje u procesu izrade knjige," " Upravljanje kvalitetom ofsetnog tiska," "Kolorimetrija u multimedijskim sustavima," and " Psihologija boja." At the Faculty of Graphic Arts, he teaches courses such as Main Printing Techniques, Offset Printing Management, Technical Editing and Production Management, Business and Security Printing, Quality Management in Printing (in English), and at the doctoral study level Advanced Printing Systems and Halftone Elements in Printing.

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I humbly dedicate this work to the profound adoration I hold for the realms of colour science and light. It stands not only for my personal passion but also as an embodiment of the ideals I wish to pass on to the generations yet to come – my future children, the cherished bearers of my strength and determination. In a special embrace of gratitude, this dedication extends to my beloved family, the cornerstone of my existence. To my father, Zeqir, a beacon of inspiration whose unwavering support and friendship have been the guiding force behind my endeavors. To my mother, Xhevrije, whose infinite patience and nurturing care have been my constant companions on this intricate journey. To my siblings, Shpend, and Albana, for my youngest brother, Albert, whose boundless enthusiasm has ignited my creative sparks. To my adorable niece, Liara Ermanila, and my nephews, Troi, Marlo Noah, and Akil, who are the embodiment of joy and purity. To the love, strength, and unity that binds us as a family.

ABSTRACT

Illuminant metamerism and observer metamerism are increasingly employed in different areas such as colour science, printing, packaging, visual perception, painting, museums etc. On artistic paintings refers to a phenomenon, where different pigments or combinations of pigments appear to match under one light source but exhibit a noticeable difference in colour when viewed under a different light source. In the context of artistic paintings, the pigments are composed of various chemical compounds that absorb and reflect specific wavelengths of light, by selecting subtractive colours from the original painting that are prone to metamerism, can have different spectral properties and interactions with lighting conditions, influencing visual system, colour perception and metamerism.

Characterizing the spectral characteristics of colour techniques and inks through colourimetric measurements, play a crucial role in quantifying and analysing metamerism by comparing the colour differences between different light sources.

Within this dissertation, research was carried out to find possibilities of reducing metamerism in different colour techniques, to standardise and reduce metamerism in perception of paintings. By using a high-quality printing process that can accurately reproduce colours, the calibration of printers was employed to ensure colour fidelity and consistency. Printing test samples on a matte paper can help minimise reflections and provide a neutral background. This research defines comparison of paintings with similar motive and half-tone reproduction sample, by providing insights into how humans perceive colour and the extent of metamerism in different lighting conditions under standardised conditions of various light sources: LED light 3000K, 4000K, 6500K, Wolfram light, and Halogen light under their Spectral Power Distributions (SPD). The task of this research was to find a scientific correlation between illuminant metamerism on paintings, made by different colour techniques and inks, such as tempera, oil, acrylic, pastel, and watercolour paintings. The study of illuminant metamerism on artistic paintings was made with objective and subjective research, with standardised condition observers assess colour matches or differences under various light sources. By using such models, one can predict how a painting will appear under different lighting conditions and better understand the factors contributing to illuminant metamerism.

Key words: Illuminant metamerism, SPD, colour perception, printing, pigments

SAŽETAK

Metamerija uvjetovana promjenom osvjetljenja sve se više koristi u različitim područjima kao što su znanosti o boji, tisku, pakiranju, vizualnoj percepciji, slikarstvu, muzejima itd. Kada se promatraju umjetničke slike metamerija se odnosi na pojavu u kojoj se čini da se različiti pigmenti ili kombinacije pigmenata podudaraju pod istim izvorom svjetlosti ali pokazuju primjetnu razliku u boji kada se gledaju pod drugim izvorom svjetla. U kontekstu umjetničkih slika, pigmenti se sastoje od različitih kemijskih spojeva koji apsorbiraju i reflektiraju specifične valne duljine svjetlosti i mogu imati različita spektralna svojstva i interakcije s uvjetima osvjetljenja, utječući na vidni sustav i percepciju boje.

Karakteriziranje spektralnih karakteristika različitih boja i otisaka putem kolorimetrijskih mjerenja igra ključnu ulogu u kvantificiranju i analizi metamerije uvjetovane promjenom osvjetljenja usporedbom razlika u boji između različitih izvora svjetlosti.

Ovaj doktorski rad fokusirao se na fenomen metamerije uvjetovane promjenom osvjetljenja u kontekstu umjetničkih slika izloženih različitim izvorima osvjetljenja. Sveobuhvatni cilj bio je pronaći optimalan izvor svjetlosti koji ublažava perceptivne nepravilnosti i poboljšava prosječnu vizualnu percepciju.

Središnja hipoteza ove teze je da prisutnost metamerije uvjetovane promjenom osvjetljenja na slikama ovisi o specifičnim tehnikama slikanja koje se koriste. Istraživanje metamerije uvjetovane promjenom osvjetljenja dalo je uvjerljive rezultate, nedvosmisleno utvrđujući da različite tehnike slikanja daju različit izgled pod različitim uvjetima osvjetljenja, potvrđujući ideju da metamerija uvjetovana promjenom osvjetljenja igra ključnu ulogu u doživljaju umjetničkih slika. Nadalje, važno otkriće leži u učinkovitosti standardizirane LED rasvjete u ublažavanju manifestacije metamerije uvjetovane promjenom osvjetljenja, posebno kada je karakterizirana dobro definiranom spektralnom distribucijom. Glavni cilj ovoga rada usmjeren je na optimizaciju uvjeta osvjetljenja kako bi se smanjile varijacije na slikama. Postalo je očito da se kvantifikacija razlike doživljaja boja temelji na temelju razlike u boji ΔE, što dovodi do upotrebe indeksa metamerije (MI) za definiranje perceptivnih nijansi metamerije uvjetovane promjenom osvjetljenja unutar domene promatranja umjetničkih djela rađenih različitim tehnikama.

U okviru ove disertacije provedeno je istraživanje kako bi se pronašle mogućnosti smanjenja metamerije uvjetovane promjenom osvjetljenja u različitim slikarskim tehnikama, standardizirala i smanjila metamerija uvjetovana promjenom osvjetljenja u percepciji slika. Korištenjem visokokvalitetnog procesa ispisa koji može točno reproducirati boje, primijenjena

je kalibracija pisača kako bi se osigurala vjernost i dosljednost boja. Ispis probnih uzoraka rađen je na mat papiru koji pomoći smanjuje refleksiji i pruža bolju percepciju sa smanjenim udjelom sjajnosti materijala.

Ovo istraživanje definira usporedbu slika sa sličnim motivom i uzorkom višebojne reprodukcije, pružajući uvid u to kako ljudi percipiraju boju i doživljavaju veličinu metamerije uvjetovane promjenom osvjetljenja pod standardiziranim uvjetima različitih izvora svjetlosti: LED svjetlo 3000K, 4000K, 6500K, Wolfram svjetlo i halogeno svjetlo, odnosno pod njihovom spektralnom distribucijom snage (SPD). Zadatak ove disertacije bio je pronaći znanstvenu povezanost između metamerije uvjetovane promjenom osvjetljenja na slikama rađenim različitim slikarskim tehnikama, kao što su tempera, ulje, akril, pastel i akvarel. Proučavanje metamerije uvjetovane promjenom osvjetljenja na umjetničkim slikama provedeno je objektivnim i subjektivnim istraživanjem, pri čemu standardizirani promatrači procjenjuju podudarnosti ili razlike boja pod različitim izvorima svjetlosti. Koristeći takve modele, može se predvidjeti kako će slika izgledati pod različitim uvjetima osvjetljenja i bolje razumjeti čimbenike koji doprinose smanjenju metamerije uvjetovane promjenom osvjetljenja. Umjetničke slike, koje su primjeri sinteze različitih kemijskih spojeva, karakteriziraju pigmenti koji selektivno apsorbiraju i reflektiraju određene valne duljine svjetlosti. Odabir suptraktivnih boja s izvorne slike, predisponiranih metameriji uvjetovanoj promjenom osvjetljenja, stvara različite spektralne vrijednosti koji su u interakciji s različitim osvjetljenjima. Time se izrazito utječe na vizualni sustav, na razumijevanje doživljaja boja i manifestaciju metamerije uvjetovane promjenom osvjetljenja. Jedinstvene karakteristike pigmenta, povezane s različitim tehnikama slikanja, daju male razlike u refleksiji svjetlosti u usporedbi s ljudskim vizualnim sustavom boja. U biti, zagonetka metamerije uvjetovane promjenom osvjetljenja nalazi se unutar domene percepcije boja, zamršenog aspekta koji uvijek može stvoriti problem u doživljaju boja kod promatrača. Iako je procjena metamerije uvjetovane promjenom osvjetljenja unutar jednotonskih boja relativno jednostavna, procjena višetonskih slika pod različitim svjetlosnim uvjetima zahtjeva uspostavljanje objektivnog mjerenja koja može kvantificirati razlike u bojama.Ovo je istraživanje potkrijepilo je izvedivost mjerenja metamerije uvjetovane promjenom osvjetljenja kod višebojnih slika analizom polja balansa sive boje, precizno reproduciranog putem empirijski testiranih uzoraka. Razlike koje se mogu uočiti unutar polja sivog balansa podložne su kvantificiranju, čime se sažima bit metamerije uvjetovane promjenom osvjetljenja putem indeksa metamerije.

Kako su se u radu istraživale različite slikarske tehnike u kombinaciji s raznim izvorima osvjetljenja, u radu je ustanovljeno da ljudi različite tehnike drugačije percipiraju kod različitih izvora osvjetljenja. Tako je ustanovljeno da se kod slika koje su rađene temperom metamerija uvjetovana promjenom osvjetljenja najmanji kada se koriste izvori osvjeteljanje s temperaturom boje u korelaciji (CCT) u rasponu od 3000 K do 4000 K.

Kod ulja na platnu, najmanja metamerija uvjetovana promjenom osvjetljenja dogodio se kod temperature boje u korelaciji između 2700K i 4000 K. Međutim ono što je ustanovljeno je također da kod ulja na platnu ljudi vide boje različitije, odnosno veća je dispergiranost promatrača i to prvenstveno u dijelu doživljaja razlike u svjetlini. Kod slika rađenih tehnikom akrila pokazalo se se da je metamerija uvjetovana promjenom osvjetljenja najmanji kada se koriste hladnije boje i to prvenstveno kod halogenog svjetla koje ima takvu spektralnu refleksiju.

Kod ove tehnike je također ustanovljeno da ljudi radi navedene temperature boje u korelaciji bolje percipiraju boje koje su toplije, odnosno kod hladnijih boja došlo je do smanjene metamerije upravo radi interakcije s temperaturom boje svjetlosti. Kod akvarela je ustanovljeno da da se boje relativno jednako percipiraju u rasponu temperature boje u korelaciji od 2700 K - 4000 K, međutim, primjećeno je da se plave nijanse na takvim slikama manje percipiraju u navedenoj temperaturi boje u korelaciji, pa se ustanovilo da je za navedenu tehniku bolje osvjeteljenje hladnijeg izvora osvjetljenja s temperaturom boje u korelaciji od 6500 K.

U kontekstu pastelnih umjetničkih djela, iako je najbolji raspon za najmanju metameriju uvjetovaua promjenom osvjetljenja, ustanovljeno je da se kod žutih tonaliteta ipak ustanovila manja metamerija uvjetovana promjenom osvjeteljnja, s tim da treba uzeti u obzir i različite izvore svjetlosti koji pokazuju drugačiji indeks metamerije u navedenom rasponu, što je detaljno objašnjeno u zaključcima disertacije.

Ključne riječi: Metamerizam uvjetovan promjenom osvjetljenja, SPD, percepcija boje, tisak, pigmenti

Objective and hypotheses of the research:

H1 Illuminant metamerism appears in paintings, depending on the painting techniques.

H2 Standardised LED light decreases appearance of illuminant metamerism with defined spectral power distribution of light.

H3 With the metamerism index, it is possible to define objective values of accepted tolerance for illuminant metamerism on different paintings.

Expected scientific contribution of the proposed research:

Illuminant metamerism appears in paintings depending on painting techniques.

Standardised LED light decreases the appearance of an illuminant metamerism with defined spectral power distribution of light.

The metamerism index can be a unit that defines the illuminant metamerism between different painting inks.

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1. INTRODUCTION

Visual perception is different for everyone. It should be noted that individual perception is affected by different factors for the selection of a particular object. The main factor of individual perception is the lighting that surrounds the environment. Human colour vision has its own impressions from the brain of how something works or how it is perceived. The perception is unique. These observers are different individuals, which suggests that perception is individual, the human brain recognises pictures that were first created by photosensitive cells in the retina. Colour is a visual perception composed of the stimulus of three types of photoreceptors called L, M, and S. cones.

The human eye often recognises different spectral distributions as the same colour since each cone has broad spectral responses. The registration of stimuli in phenomenal consciousness is visual perception. Traces at unconscious levels of processing are left by unperceived stimuli that can affect visual perception and performance. [1]

When it comes to visual perception of an object, our brain performs computation that outclasses the most sophisticated modern computers, and each time we open our eyes, we make sense of the pattern of light reaching the human retina. [2] Perceiving electromagnetic radiation is a subset of the optical spectrum that enables the human eye to be a sensory organ. [3] Common factors of visual perception may be the cause of a similar perception. The illumination of light, illuminant metamerism, and observer metamerism show this best in terms of individual perception. Luminous changes indicate a change in perception.

This research proposes a method to evaluate the ratio of the mixture of dyes that can cause metamerism. The purpose of this research is to present how colours are perceived by different individuals - by using 3 subtractive colours in different colour technique and to generate illuminant metamerism under different sources of light, to thus enables the representation of premeditated colours.

Paintings as artworks have the highest light sensitivity in museum lighting. Therefore, photochemical damage such as fading, and discolouration may be irreversible. [4] The spatially variable spectral reflectance factor, the surface macrostructure, and the surface microstructure are included in a complete physical description of paintings. [5]

In artistic paintings, it is possible to match a wide range of colours by using a combination of three fixed colourants (red, blue, and yellow) for a particular observer and light source. [6] The

CIE International Commission on Illumination. Scotopic vision and photopic vision are two types of vision; the first one has to do with the rods mediate vision when very little light is available, 0,2-30lx, and photopic vision is defined by the proxy of cones when vision is sharp, under luminous conditions of over 30lx. [7] Perceptually approximately uniform colour space is the CIE L*a*b* colour space (Colourware Ltd 2001: International Commission on Illumination 1996). This colour space was intended for use with surface colours. [8] The CIELAB space is determined to be acceptable in many real-world applications despite its theoretical challenges. However, if the aim is a photographic reflection that prints a picture, this is frequently unsatisfactory, since our visual system adjusts its judgment regarding the "perceived" lightness based on the illumination geometry in the scene. Colour stimuli with the same tristimulus values but different spectral radiant power distributions are, in fact, metameric colour stimuli.

These definitions are termed metamers and the basic concept is referred to as metamerism. [9] Depending on the dominant tones, a phenomenon often occurs that results in the dissatisfaction of the end user with halftone colour reproduction, and this phenomenon is called Metamerism. [10] Obtaining paints that cause metamerism under the desired light source is difficult for the average person, despite the colour charts that are available commercially to confirm metamerism. [11] Colourimetric coordinates are supposed to be the most common metamerism indices.

The degree of metamerism is described by the indices that are based on the spectra deviation of a metameric pair or the difference in colour of the pair under test conditions. The evaluation of the magnitude of illuminant metamerism is commonly represented by the measurement of the colour difference under the test illuminant. The colour differences calculated by the selected test illumination are different; in this case, the measured (social) metametrism index could be considered as the test illumination-dependent value. [9] It was assumed that metamerism would not be a problem under various real sources [e. g., Billmeyer (1963)], if a pair of metameric samples matched for both D65 and A source of light. According to the definition, each set of metamerism that is matched under CIE illuminant D65 for the 1964 CIE standard observer under a test illuminant would be mismatched, forming a gamut of colourimetric coordinates.

These gamuts of metameric mismatch were quantitatively evaluated using multivariate statistics [12]. Two specimens are metameric only if their spectra are different in the visible region and if they have identical tristimulus values for a single condition of illumination and views, according to the CIE. [13] A different colour from the observer for the same item is produced when the light source is changed. [14]

There are many facts that present the standardisation of LED light. The improvement of modern light has been continuing across the spectrum, and the most promising one for the 21st century is no doubt the LED light, which has 2-4 times more useful lifespan than that of their average competitor, while producing high-quality light much more efficiently. Compared to light bulbs, light-emitting diodes have improved their efficiency by roughly 50%, LEDs are highly energy efficient – less heat, more light, lower cost, LEDs do not contain mercury and do not emit UV rays., Unlike fluorescent bulbs, which waste most of their energy in the form of heat, LED use 100% of their energy to produce light. The LED lightning system fits perfectly into the decor of the space, most LED fixtures are made of high-quality, eco-friendly plastics.[15]

The strengths and weaknesses of monochromaticity of a LED light are reflected by its spectral characteristics. Many LEDs cannot produce monochromatic light at a wavelength peak, so the term ‘dominant wavelength’ is introduced aiming to describe the spectral properties of LEDs. The wavelength of the main monochromatic light defines the dominant wavelength, and it is observed by the human eye. The LEDs have only one dominant wavelength, even though some LEDs give multiple wavelengths of light. [16] As monochromatic light sources, LEDs are more advanced due to their miniature footprints. Using these devices for colour mixing is much more feasible compared to conventional light sources, which are obviously of larger dimensions. [17] Light-emitting diodes, known by the acronym LED, are sources of radiant energy characterised by solid state. This radiant energy produces material in a light-emitting diode, a prepared semiconductor material, where small amounts of chemical compounds are added as controlled impurities. These impurities are used as two types. One is known as the n-type, which yields a semiconductor material and has an excess of electrons. The LED has a spectral radiant distribution and is confined to a narrow spectral region. The semiconductor material and the added impurities are two things that the wavelength of LED peak emission depends on. The light-emitting diodes are very small physically.

The dimension of the semiconductor chip of the pn junction generally ranges from 0.2 to 1mm square; 2 to 5mm is the size of the assembled source, which varies depending on its design and construction. [8]

1.1 Light

Light refers to electromagnetic radiation that is visible to the human eye. It is a form of energy that travels in waves and is characterized by its wavelength and frequency. Light plays a fundamental role in various scientific disciplines, including physics, chemistry, biology, and optics. The term electromagnetic wave is a kind of electromagnetic radiation which is directed at the rays of a source and transmitted over a given area of the environment. It can be characterised by measuring an electromagnetic wave's frequency (f) or wavelength (λ), The International System of Units (French name Le Systéme International d' Unités abbreviation of the SI,) uses hertz (Hz) as the unit of frequency and the metre (m) as the unit of wavelength. As shown in the following equation, the frequency of a wave, or the number of waveforms passing a specific location in a second, is inversely proportional to its wavelength.

$$f = \frac{c}{\lambda} \tag{1}$$

where the speed of light in a vacuum is c = 299,792,458 m/s. [18]

The wavelength describes the light for which the nanometre (nm) represents a convenient unit of length. Light can be moved as a wave or as a particle photon. The most common basis for visible light in fact, is electromagnetic radiation, just like microwaves, to high-frequency X-rays and all other as shown in (Figure 1), through which visible radiation is considered to have a lower limit between 360 and 400 nanometres and an upper limit between 760 and 830 nanometres. [19][20] The specific wavelength through rays determines the colour and intensity determine the source of light. If the wavelength is longer than the visible spectrum, for instance, on waves of IR-infrared, our eye cannot catch them. If the wavelength is shorter than the UV rays, again it is impossible to see them. Other species have a bit different ray of vision, but the visible spectrum is for mankind. According to Sliney, D. H., Wangemann, R. T., "*This is the part of the electromagnetic spectrum that mankind has evolved the ability to perceive. However, under laboratory conditions, the human eye can detect even longer wavelengths, up to 1064 nm.*" [21]

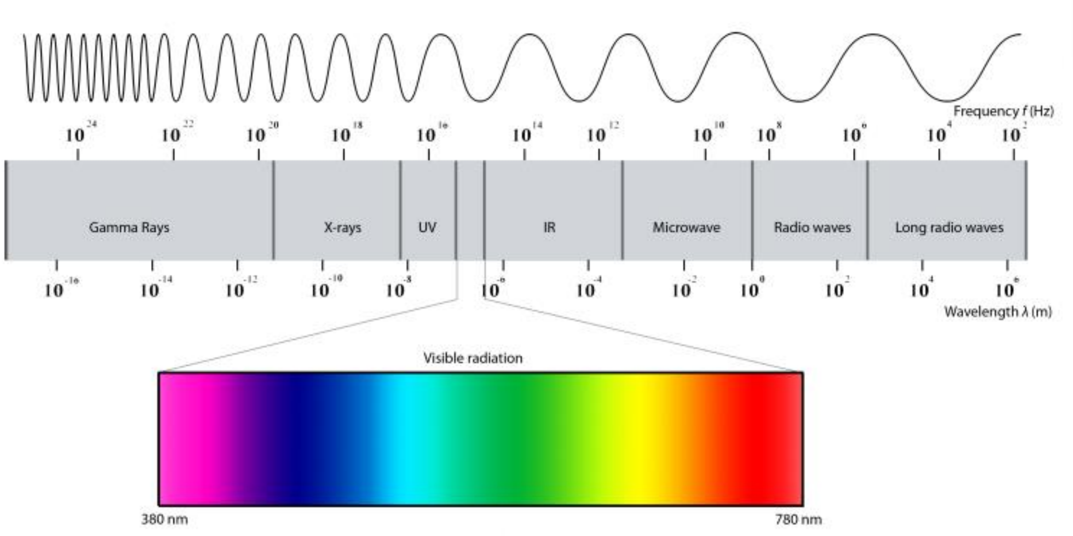


Figure 1. Electromagnetic spectrum, visible radiation is approximately between 380 and 780 nm in this spectrum [19]

Essentially, light is the visible radiant energy that awakens the observer through visual experience. [22] Issac Newton divided white light into its constituent colours in 1666 using a glass prism. Newton gave this range of unbroken hues the name spectrum, which is a translation of the Latin word for "appearance" or "apparition". [23]

1.1.1 Black-body radiation

Shortly and Williams (1974 pp. 323-326) gave a definition of Black Body radiation describing it through the temperature of materials that above zero, radiation is emitted.
The solid temperature radiates an energy that increases rapidly; therefore, the emitted radiant power depends on the character of the solid surface. Max Planck tried to find out precisely the black body radiation, experimenting with a box with a small hole, heating it, and waiting for the system to reach a fixed temperature to see what kind of electromagnetic radiation comes out of the hole. Trying to apply classical mechanics to this problem, Rayleigh, and Jeans, who calculated correctly, asserted that the black body would emit electromagnetic radiation, having a distribution of frequencies. Therefore, the higher the intensity is when the frequency becomes larger, and thus the ultraviolet comes to be an absurd conclusion. [25] The spectral exitance, or

the radiant flux of blackbody radiation emitted by a surface per unit area per wavelength, is how Planck's law states, $M_{e\lambda}$ is given by,

$$M_{e\lambda} = \frac{2\pi hc^2}{\lambda^5}\left(\frac{1}{e^{hc/\lambda kT} - 1}\right) \tag{2}$$

where T is the temperature in Kelvins (K), h is the Planck constant (6.6256 ± 0.0005) x 10^{-34} joules seconds (Js), and k is the Boltzmann constant, which is 1.3807 x 10-23 J/K. [24][26][27]

1.1.2 Radiometry and photometry

The scientific study of measuring radiant energy, including its distribution, intensity, and spectrum content, is known as radiometry. Many disciplines, including remote sensing, atmospheric science, and materials research, are dependent on radiometry. When electromagnetic radiation is measured, its radiant energy and the geometry of how it travels across space are determined. The measurement of electromagnetic radiation using photometry is similar, and only considers visible radiation. [26]

The radiant energy Q_e per unit time t is known as the radiant flux (radiant power) Φ_e, the time rate of flow of radiant energy (unit: watt), spread from a source is explained in the equation below according to McCluney, W.R., (2014):

$$\Phi = \frac{dQ}{dt} \tag{3}$$

The measurement of light, including its brightness, colour, and distribution, is the subject of scientific fields of photometry. [27] Many disciplines, such as lighting design, vision science, and astronomical imaging, depend on photometry. The watt is the unit of radiant flux (W). The luminous flux is the photometric unit that corresponds to the radiant flux. It includes the unit of lumen (lm),

$$\Phi_v = K_m \int_{380}^{830} \Phi_{e,\lambda} V(\lambda)\, d\lambda \tag{4}$$

where under photopic circumstances, the spectral luminous efficiency function V (λ) represents how the human eye reacts to light intensity. [27] The radiometric and physiological variables are related to the constant Km = 683 lm/W. The wavelength at which V (λ) peaks at 1W, thus, a monochromatic light source with a wavelength of 555 nm produces radiant flux with a luminous flux of 683 lm. [26] [27]

1.1.3 Spectral power distribution

Spectral power distribution (SPD) refers to the measurement or description of the power of light at each wavelength across the entire electromagnetic spectrum.

According to Schanda, J., & Danyi, M. (1977):
"*The amount of power emitted by a light source per unit wavelength is known as the spectral power distribution (SPD).*" [28]
It is also known as the relative spectral distribution of S (λ), as it shown in the equation,

$$S(\lambda) = \frac{X_\lambda(\lambda)}{R} \tag{5}$$

The radiant flux per wavelength is $X_\lambda(\lambda)$, and R is defined as "a fixed reference value, which may be the maximum, average, or arbitrary value of this distribution (CIE, 2011). [29]
The optical power distribution refers to the measurement of how the power of a light source is distributed over different wavelengths or frequencies of light. In other words, it describes how much energy is present at each wavelength in a light source. Some notable contributors to our understanding of spectral power distributions include Max Planck, who developed the theory of quantum mechanics in the early 1900s. Other important figures in this field include James Clerk Maxwell, who developed the theory of electromagnetic radiation, and Johannes Kepler, who conducted early experiments on the properties of light. [27]

1.1.4 Correlated colour temperature – CCT

The correlated colour temperature is referred to as the distribution temperature if the relative spectral power distribution of the source correspondent corresponds to the point on that Planckian locus according to the CIE vocabulary. [28][30] The relative power distribution is not perfectly replicated by most sources, but many of them share its chromaticity, in which case the temperature of the latter is called the colour temperature (Figure 2).

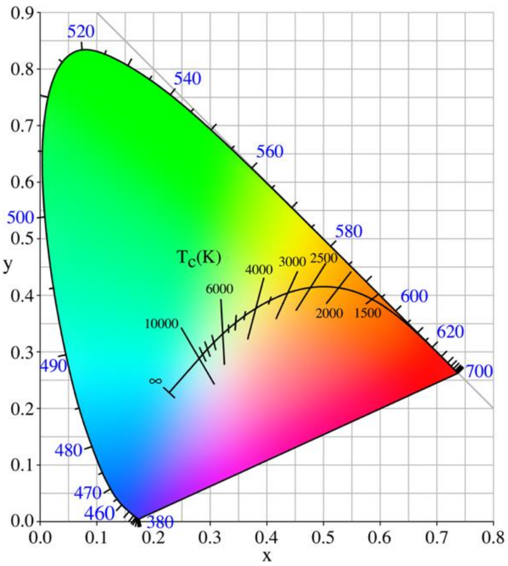


Figure 2. The CIE 1931 x, y, chromaticity space also exhibits a line of constant associated colour temperature and the chromaticity's of black-body light sources at varying temperatures [29]

A curved line known as the Planckian locus is used to depict the chromaticities of Planckian radiators at various colour temperatures in the x, y, chromaticity diagram. The corresponding colour temperature is calculated for sources that do not locate on the Planckian locus as the colour temperature whose chromaticity is closest to the source's chromaticity on the x, y, diagram. [25][27][28] [29]

1.2 Light Sources

1.2.1 History of light

Lightning is known to have made its rapid revolution in all areas of human life. Daylight refers to the natural light that is present during the day when the sun is above the horizon. Bright natural light that illuminates our surroundings during the day, allowing us to see and perform tasks without relying on artificial light. The light varies in intensity and colour depending on factors such as time of day, season, weather conditions, and geographical location. It is essential for our physical and mental well-being, as it helps regulate our circadian rhythms, which affect our sleep-wake cycle, hormone production, and other bodily functions. [31] Three components constitute daylight: direct sunlight, diffuse sky radiation (also known as skylight), and sunlight and skylight reflected off the Earth or objects on the ground. [32] Beyond visible light, X-rays, UV, IR, and radio waves are also included in solar radiation. [33] The effective temperature of the sun, or the temperature at which a black body would produce the same total quantity of electromagnetic radiation, [34] as the sun is around 5777K, according to the National Aeronautics and Space Administration (NASA). [35]

One of the most brilliant ideas for using the sunlight inside an object was of course the Pantheon, which is an outstanding architectural work from the Roman Empire, where it is designed almost entirely around the open-air circle at the top of its dome. Since then, the human mind has continuously been trying to find more efficient ways and methods of lighting specific objects and areas. Lightning, as one of the most essential elements in life of every species on earth, has its evolution and, of course its irreplaceable role. Compared with the Internet as an important part of modern life, lightning has always been a significant part not only for human beings but also for all creatures on Earth, meaning here for the natural light source, the Sun. The fact that this source of light is present only in a specific part of the day, not 24 hours, has made it necessary to have light during the night and in places where the light of the Sun cannot be penetrated, such as caves in prehistoric times. Hereby, at that time, the first artificial source was fire and then candles. Imagine such a long time ago, that there was a long way to go for light as it is today.

Another way of lightning in prehistoric ages was the making of torches which is supposed to be used in 70.000. This type of lamp was made of shell, hollowed-out rock filled with dried grass or wood; later, wax or some kind of oil was used, surrounded by non-flammable material.

Candles were shown as another source of lightning, as results of human efforts to invent something more practical to be used. Here, we have to do with the use of wax beeswax or tallow (a derivative of animal fat), which then represented the most significant technological lighting advancement since the discovery of fire itself. The first holding candles are supposed to be used in the fourth century B.C., in ancient Egypt, the Roman empire, and the Greeks, but the Asian countries of that time were separately making candles out of whale fat as early as 200 B.C. [36]

1.2.2 Incandescent light source

The major advancement in lightning, gas lamps and electric lamps to come; 1790 was the year when gas lamps have been developed in England, the electric lamp was another advancing step in lightning, created by Englishman Humphry Davey who ‘debuted the first incandescent light to the Royal Institute of Great Britain, using a bank of batteries and two charcoal rods’, according to the US Department of Energy). [37] [38]

When an object is heated to glow, incandescent light is emitted. The object’s heating temperature, specifically white light, is 1,341°F (727°C).

The basic principle of all incandescent lamps working is that light is emitted through a high enough temperature by electricity running through thin strips of metal. This invention was shown by Sir Humphrey Davy in 1802. This invention was followed by de La Rue, who demonstrated a further process of this kind of lighting, by a lamp made of a coiled platinum wire in a glass tube with brass end caps. Electricity was passed through the end caps and the wire when the current was switched on. The resistance of the wire to the current, heated it until it glowed white-hot, and light is produced. At that time, these lamps were unsteady, expensive, and had short-term function. The reason for the short lifetime of these lamps was the fact that the filament could burn up in the air.

The early researchers of this time, such as Thomas Edison, Joseph Swan, Frederick De Moyleyns, Moses Farmer, Hiram Maxim, and William Sawyer, gave their contribution in this field. Thomas Edison was well known for the invention of the light bulb.

On 22 October 1879, who set out this invention, his prototype incandescent light burnt for thirteen and a half hours.

This invention marked the revolutionary advancement of lightning technology. [39] The alternating current and cableless power transmission are credited to Nikola Tesla, the inventor.

The transmission of non-wired energy by electromagnetic waves (oscillations) in the industrial alternating current frequency band (102-109 [Hz]), which overlaps with radio frequencies, and the transmission of energy through monophase, biphasic, and polyphase alternating currents are attributed with this. [40]

1.2.3 CIE Standard Illuminant A and Planck radiation

According to the CIE standard draught [41], it is as follows:
Typical domestic tungsten filament lighting is represented by the CIE standard illuminant A. The Planckian radiation at a temperature around 2856K represents its relative spectral power distribution. Unless there are specific reasons for using a different illuminant, use of incandescent lighting is used in all applications of colourimetry using the CIE standard illuminant A. [41] Blackbody radiation approximates well the radiation of a coiled tungsten filament incandescent lamp, one of the radiations for which SPD can be described using fundamental physical laws and constants. [42][43] Radiant exit spectral concentration is described by Plancks radiation law [44], M_e, in W/m^3 (power per source area of source per wavelength interval) as the function of wavelengths, I, in metres and temperature, T, in Kelvins, by the equation,

$$M_{e,\lambda}(\lambda, T) = \frac{c_1}{\lambda^5 \cdot \left[\exp\left(\frac{c_2}{\lambda \cdot T}\right) - 1\right]}, \text{units W/m}^3 \tag{6}$$

were,

$$c_1 = 2\pi \cdot h \cdot c^2 = 3.74183 \times 10^{-16}\,\text{W/m}^2,\ c_2 = h \cdot c/k = 1.4388 \times 10^{-2}\,\text{m} \cdot \text{K} \tag{7}$$

c is the speed of light in vacuum, h is the Planck constant, and k is the Boltzmann constant. [42][45] The CIE standard illuminant A, with the above values of c_1 and c_2 a temperature of 2856K, has the same relative spectral power distribution as a Planckian radiator illuminant A's relative spectral power distribution is $S_A(\lambda)$, [26]

$$S_A(\lambda) = 100\left(\frac{560}{\lambda}\right)^5 \times \frac{\exp\frac{1.435 \times 10^7}{2\,848 \times 560} - 1}{\exp\frac{1.435 \times 10^7}{2\,848\ \lambda} - 1} \tag{8}$$

The relative SPD determined by this equation is the same as the relative SPD established in 1931. [26][29][46]

1.2.4 Halogen light

The invention of halogen light came because of engineers' efforts to find a way to invent a lamp that would last longer than an incandescent lamp and to give brighter light while consuming less energy. This is determined by the lasting of a filament, and if evaporation the filament is reduced, the life of the lamp will be longer. The lamp will shine brighter if the temperature of the filament is increased. Therefore, the halogen lamp was the better solution. A carbon-filament lamp containing chlorine was invented by Edwin Scribner of the United States Electric Lighting Corporation (USELC) and was granted a US patent in March 1882, but it was removed from the market in 1894. [47] The first commercial halogen lamp was introduced in 1959 by General Electric (US Patent 2,883,571), being developed by Elmer Fridrich and Emmet Wiley, who worked there. They have improved halogen lamps to be lighter since 1980. [48]

An incandescent tungsten lamp, called a halogen lamp, contains small amounts of halogens such as iodine or bromine. When the halogen gas migrates back toward the centre of the lamp and interacts with the evaporating tungsten, it deposits the metal back onto the filament. The halogen cycle is the name of this ongoing cycle. [23] [26]

Halogen lamps are of two variants: one-sided and two-sided. Used as floodlights, work lights, and film production lights, two-sided halogen lamps have stronger light and take more power. Having strong light and small size, one-sided halogen lamps are used in museums, automobile headlights, film projectors, and in homes as general lighting.

These lamps can be characterised at high temperatures around 2850 to 3300K, with a higher efficiency around 15 lm/W to 35 lm / W, [23] because they have smaller surfaces that cool less and are closer to the filament.

1.2.5 Light Emitting Diodes – LED

The most promising for the 21st century is evident to be Light Emitting Diodes (LED) lightning, for its solid-state light that does not require glass housing like traditional bulbs and produces light-converting electrical current using a semiconductor. Nick Holonyak was the scientist at General Electric who invented the LED in 1960. When you see the high improvement of LED in every field of life, LED has become the modern light of the 21st century. [49]

Light-emitting diodes, known by the acronym LED, are sources of radiant energy characterised by solid state. This radiant energy produces material in a light-emitting diode, is a high purity semiconductor material prepared, where small amounts of chemical compounds as controlled 'impurities' have been added to these impurities, of two types; one is known as n-type, which yields a semiconductor material with an excess of electrons. The other type of impurity is known as p-type material that has a shortage of electrons or holes. [50]

The strengths and weaknesses of the monochromaticity of a LED are reflected in its spectral characteristics. Monochromatic light cannot be produced by many LEDs; it is not only one wavelength peak, so the term 'dominant wavelength' is introduced to describe the spectral properties of LEDs. The wavelength of the main monochromatic light defines a dominant wavelength and is observed by the human eye. There is only one dominant wavelength that an LED has, even though some LEDs can give multiple wavelengths of light. [51] Having a longer operating life and much better efficiency than tungsten lamps, LED lamps are solid state devices and are rugged.

The use of LEDs as reference light source is being set up under CIE, by a technical committee because LED lamps have different spectral power distribution. A reference spectral for LED standard lamps named illuminant L was decided by the committee [52].

In recent years, there has been a rapid development of light-emitting diodes (LED).

This development is marked by the wide utilisation of LED in daily life, such as museum and gallery lighting, indoor lighting outdoor lighting, special lighting, monitor and backlight.

More attention is paid to the requirements of good performance in high light efficiency and high quality of light distribution because of LED development. [53] Also, they have a long life of more than 100,000 hours.

The CIE is trying to standardise the methods for describing and evaluating the characteristics of LEDs and LED cluster arrays. [54] [55]

2. COLOUR VISION

2.1 Physiology of colour vision

We get information through the five senses. All these senses send information to the brain. Colour is the perception of light that can be described and identified only through the sense of sight. A certain object can be described without the presence of light by its form and composition, but colours as an abstract thing cannot be touched, so they cannot be defined without light. The eye is the only sense of first contact with light. Light colours are permanent, where the colours of objects are unstable. Light transmits colour in different ways.

Depending on individual perception, colour is seen in different ways by different observers.

It is enabled to describe colour through referential to physical processes such as the production of stimulus in the form of light, including here directly and indirectly by interacting with a material, and subjective outcomes such as receiving and interpreting this stimulus in the eye and brain or generally visual system. These latter effects are more significant to observers based on the existence of colours in the mind of the viewer. Moreover, to understand them, the visible spectrum must be considered. [56] [57] [58]

2.1.1 Human visual response

Through eye structure, the mechanism which the information is transmitted in the brain and how the information is interpreted onto the brain is clearly and closely seen. Vision or sight is based on the interaction of light with the eye. The cornea is the transparent frontal part of the eye. Around two-thirds of the eye's optical power comes from the cornea. [59] Due to the difference in the index of refraction between the cornea and air, the cornea, which has a curved surface, serves as the main component of the refractive system.

The coloured portion of the eye, the iris, is located behind the cornea. The pupil is a hole in the centre of the iris that is controlled by it. Iris fixes the amount of light that penetrates through it and determines how much light enters the eye. It can be seen when the pupil changes form to fix the intensity of available light. Tightening is called when this part of the pupil is diminished, and extension is called when it becomes bigger. Due to the light rays passing through the eye, the pupil appears dark. Behind the pupil is the lens that concentrates the light above the retina. The pupil of the eye allows light to enter the eye. Although the amount of light in the retina usually determines the size of the pupil, other factors, such as the spectral and time properties of light, the size and area of the retina activation, and nonvisual events, such as emotional reactions, also affect the pupil response. [60] The cross-section of the human eye's optical axis and visual reaction is shown in (Figure 3).

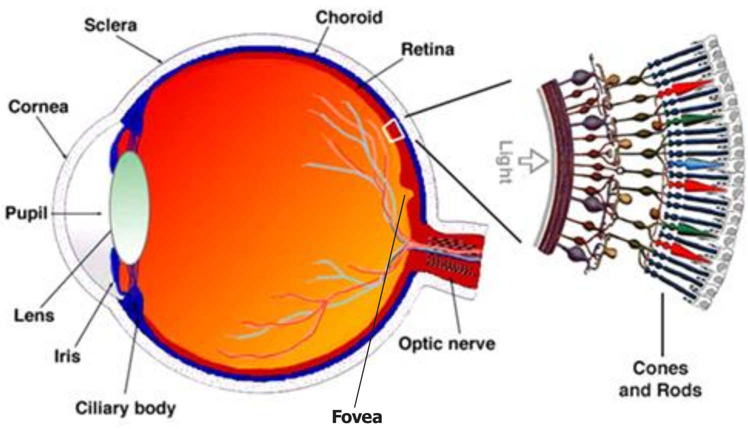


Figure 3. Optical axis of the human eye [196]

The photoreceptors found in the retina absorb some of the light that hits them and produce a signal that the brain eventually decodes. The process of forming a picture is very similar to how a camera works. Depending on the absorption, focussing properties of the cornea, scattering, lens, and fluids that fill the eyeball, it has an impact on the quality of the retinal image. [58]
Rods and cones are two types of receptors that are distinguished by their shapes. They are found in the retina and together form the retinal mosaic and synchronise circadian rhythm. [61] They are distributed differently in each retina and between individuals. The fovea, also known as the foveal pit, is a depression in the retina located in the centre of the eye. There are only cones in this area. Foveal vision is used to identify extremely fine details, such as when reading or viewing items from a distance. [58] The amount and purpose of the two main groups of photoreceptors, rods, and cones differ. In a typical human retina, there are 90 million rods and 4 million cones. [62]
The rods, which are outside the fovea, are around 100 times more sensitive to brightness and allow vision at low luminance levels (less than about 10-3 cd/m2) (CIE, 1994). [63]

The cones are the colour sensors in our eyes. The world turns from grey to colour as the sun begins to rise in the morning. We have three different types of photopigments, each of which reacts to light differently depending on its wavelength, and these pigments are what give us our perception of colour. Different cone signals lead to distinctly coloured stimuli. Instead, there are interconnections between horizontal, bipolar, amacrine, and ganglion cells, which structure receptive fields, each of which forms receptive fields; each cone does not have a unique connection to the brain. [64] [58]

2.1.2 Trichromacy theory

The three cone types are denoted by the letters L- long, M- medium, and S- short, with the wavelength sections serving as their respective peak sensitivities. [58] According to Mark Fairchild (2013) [65], the relative quantity of L, M, and S cones is around 40:20:1.
Their spectrum sensitivities, especially those of the L and M cones, overlap quite a bit. As a result, colour perception is improved. The distance between the S and M cones is another. Spectral differences are rarely used to forecast visual differences, as the spectrum is not sampled consistently. When two stimuli create the same cone signals, regardless of whether they are lighted objects or coloured lights, they are identical in colour, as shown in (Figure 4). Knowing the spectral sensitivity of the cones and the spectra of the stimuli allows one to calculate the colour matching. [46]

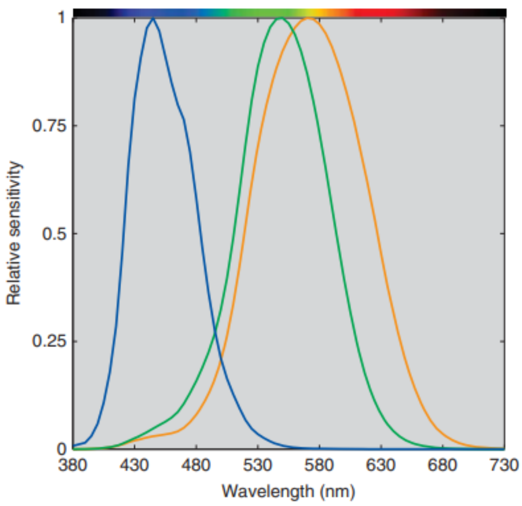


Figure 4. Spectral sensitivities of the human visual system correspond to the L, M, and S cones, respectively [46]

Two different processes: the trichromatic theory at the photoreceptor level and the opposition theory from the ganglion cell onwards, can be explained for the fundamental of colour processing in the visual system. Thomas Young is commonly given credit for the trichromatic colour theory, which proposed that consequences of the signal from the three different types of photoreceptor cells can result in colour vision (1802). [66] Helmholtz, extending Young's theories, carried out colour matching experiments in 1866 to demonstrate that any light may be matched by a combination of three different primary lights [67] [26]. Even though there is proof that several scientists and technologists predicted trichromacy in the 18th century, including Palmer in 1777. [68] [58]

The transformation of spectra into trichromatic signals is shown in the equation below,

$$L = \int_\lambda S_\lambda R_\lambda l_\lambda \, d\lambda$$
$$M = \int_\lambda S_\lambda R_\lambda m_\lambda \, d\lambda$$
$$S = \int_\lambda S_\lambda R_\lambda s_\lambda \, d\lambda \tag{9}$$

where S_λ is the spectral power distribution of an illumination source, R_λ is the spectral reflectance factor of an object, and l_λ, m_λ, S_λ are the spectral sensitivities of the human visual system. One of the most crucial aspects of the visual system is the trichromacy process, which transforms spectra into three signals. This implies that the same trichromatic response can be generated by different spectra. This phenomenon is called metamerism, there are several instances, especially visual ones. [69]

2.1.3 CIE 1931 XYZ Colour Matching Functions

The human visual system's reaction to light of various wavelengths is described by a collection of mathematical formulas called the CIE 1931 XYZ colour matching functions. They are a standard in colour science and were created by the Commission Internationale de l'Eclairage (CIE) in 1931. [44] [50]

The three types of cones in the human eye react to various light wavelengths in different ways, which are described by the CIE 1931 XYZ colour matching functions. The colour matching functions define the proportions of light that must be combined to produce a perceived colour in these cones, which are sensitive to short (S), medium (M), and long (L) wavelengths. [50] Several colour spaces, notably CIELAB and CIEXYZ, that have applications in colour science and colour management, are based on the CIE 1931 XYZ colour matching functions.

2.1.4 Colour deficiency

In trichromatic theory, three lights are taken to make a match. Trichromatic theory explains the predicted fact that what happens if a person loses one of the cone classes in their retina is called colour deficiency. In this case, the problem for these people is not that they cannot see colours, but they cannot distinguish between hues, as the people of three cones can.

Individuals with this deficiency cannot distinguish reds and greens, so, based on plentiful data, this is due to the loss of M or L-cones. Another deficiency, known as being unable to distinguish blue and yellow, is the result of loss of S-cones. [70] A colour vision test called the Ishihara test is used to identify red and green colour deficits, to identify observers with standard and deficiency (Figure 5).

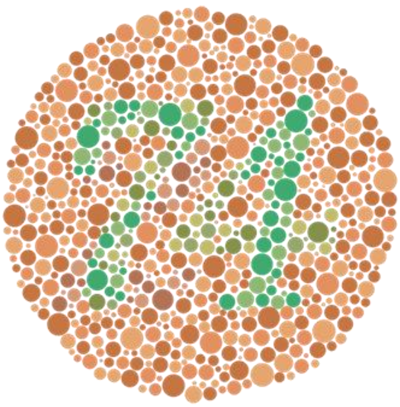


Figure 5. Example of testing for standard and deficiency observers [72]

It was given that name in honour of its creator, Professor Shinobu Ishihara of the University of Tokyo, who initially published his tests in 1917. [71][72]

3. METAMERISM

3.1 Definition of Metamerism

There are numerous definitions for metamerism, but Jud and Wyszecki (1963) defined metamerism as follows:

Metameric colour stimuli are colour stimuli with the same tristimulus values but different spectral power distributions. An equivalent definition states that metameric colour stimuli are colour stimuli that have different spectral radiant power distribution but match in color for a given observer. Metameric colour stimuli, as defined above, are often referred to as metamers, and the underlying concept is referred to as metamerism. [73]

A phenomenon known as metamerism occurs when the colour of two objects appears to be the same under a specific light source but really has different spectral power distributions. The colour difference between them may be seen when a different type of light source is used. Metameric objects are those that, when illuminated by a given reference illuminant, reflect stimuli of different spectral power distributions (SPD) that produce the same colour under the same viewing conditions. [50][74]

3.1.1 Metamerism fields

According to Wyszecki, 1985, there are four types of metamerism:

1) Illuminant Metamersim
2) Observer Metamersim
3) Geometric Metamerism
4) Field-size Metamerism

3.1.2 Illuminant Metamerism

The CIE definition of illuminant metamerism is exemplified by two specimens with unequal spectral radiance distributions within the visible spectrum that have identical tristimulus values for a given reference illuminant and reference observer. When the reference illuminant is replaced with a test illuminant, a tristimulus mismatch may occur. [73][58]

Each light source has its own emission spectrum (colour), so when a light source is projected onto a surface, the surface colour is influenced by the colour of the light. [75] The term has a related meaning; considering in the field of reflecting samples, metamerism in this case is distinguished due to the possibility of surfaces to change perceived colour, thereby altering the spectral characteristics of the illuminant. The proposed metamerism indices depend on the assessed change in colour of specific surfaces changing the illuminant, calculated by procedures that are similar to those used for the colour rendering index of illuminants, and on the number of intersections of the assessed samples spectral reflectance functions. Two samples are metameric as the result of intersections of these functions at least three times, whereby the degree of metamerism is lower when there are more intersections, thereby implying more resistance to colour change by illuminant changing. [76]

Metameric colour stimuli are those that have the same tristimulus values but distinct spectral radiant power distributions. The term "metameric stimuli" refers to colour stimuli that are similar in colour to a particular observer but have varied spectral radiant power distributions. The term "metamerism" refers to both the fundamental idea and these definitions. The different spectral radiant power distributions of two metameric colour stimuli are indicated by the letters P1 and P2 and must satisfy the following equations [50] in quantitative colorimetric terms:

$$\int_\lambda P\_1\lambda\, \bar{r}(\lambda)d\lambda = \int_\lambda P\_2\lambda\, \bar{r}(\lambda)d\lambda$$
$$\int_\lambda P\_1\lambda\, \bar{g}(\lambda)d\lambda = \int_\lambda P\_2\lambda\, \bar{g}(\lambda)d\lambda$$
$$\int_\lambda P\_1\lambda\, \bar{b}(\lambda)d\lambda = \int_\lambda P\_2\lambda\, \bar{b}(\lambda)d\lambda \quad (10)$$

This happens because the spectral makeup of the light source can alter the way colours seem to our eyes. Colour perception is a complex process that involves the interaction of light, the object being observed, and the human visual system. When light strikes an object, some wavelengths are absorbed, and others are reflected.

In summary, illuminant metamerism is a phenomenon in colour perception where two colours look the same under one lighting condition but different under another lighting condition [77]. This occurs because the spectral composition of the light source affects the way our eyes are, perceive colour, and can have practical implications in various places such as museums and industries where colour matching is essential. The change of SPD and CCT in lighting occurs with an illuminant metamerism as shown in (Figure 6).

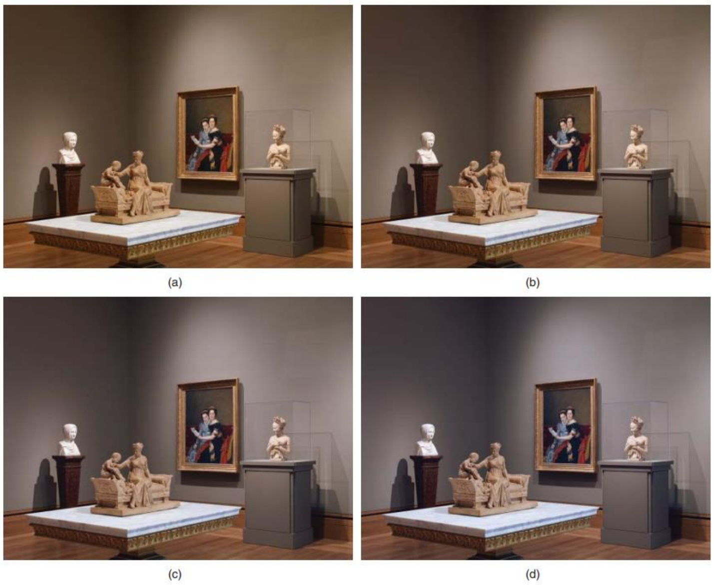


Figure 6. The Getty Museum in Los Angeles, Gallery of late Neoclassicism in European art and design. The various types of lighting are (a) soft, (b) bright, (c) cool, and (d) daylight. [58]

However, if the lighting conditions are different during the painting or printing process, the final product may look different than intended, while the particles are placed in a different environment and light conditions. [58] For example, in printing, colour matching is essential to ensure that the final printed product matches the original design. [77] Although this is not the only request when we have present illuminant metamerism (Figure 7), due to the different specifics of lighting conditions such as SPD, CCT, Colour rendering index (CRI), Lux, etc.

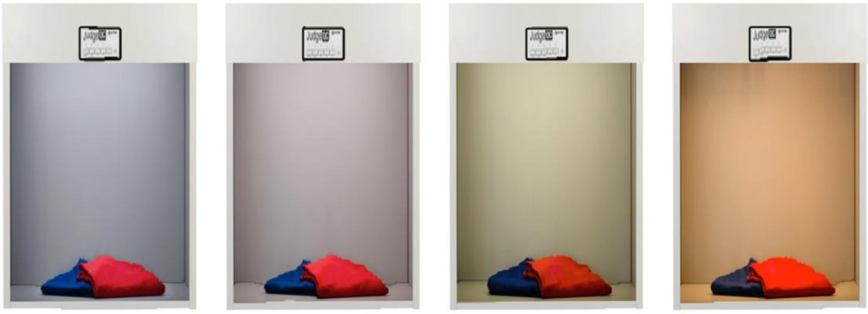


Figure 7. Illuminant metamerism due to the change on different SPD, CCT, CRI, Lux [197]

3.1.3 Observer metamerism

If identical tristimulus values are produced, metameric stimuli with respect to a given observer are object colour stimuli of different spectral radiant power distributions. The two stimuli being in a complete colour match is judged by the given observer. [78] This type of metamerism has to do with different observers when metameric pairs are observed by the eyes of an individual and mismatched by another, which is significant not only in determining the acceptability of perceived colour differences in metameric pairs, but also in illuminant metamerism, as the reference in the evaluation. [50]

The special metamerism index: change in observer, also abbreviated as "observer metamerism index," is a metric of observer metamerism (as proposed by the CIE) [3]. It is essentially the CIELAB colour difference between the metameric samples (under illuminant D65) as perceived by the CIE standard-variable observer. [79] When the illuminant or the observer changes, then the larger the spectral differences, the larger the colour mismatch. Because of the limitation to the case in which the illuminant is changed, the special metamerism index is, in fact, the CIE metamerism. [50]

3.1.4 Geometric metamerism

This type of metamerism refers to two object colours, matched under one set of conditions, which no longer match when the geometrics of illumination and viewing are changed. This is due to the differences between gloss and texture of the two members of the pair. [50]

3.1.5 Field-size metamerism

When the match fails because of the the size of visual field or distance viewing, then we have to do with field-size metamerism. [80] For the same observer different sets of colour matching functions are used in this case for the fields of 1-4 ° and above 4 ° angular subtense different sizes of visual field are used. [50] [81]

3.1.6 Metamerism index

Colorimetric coordinates are supposed to be the most common metamerism indices. [58] A reference condition and a test condition are defined, in the first one the metameric pair matches, and in the second one (a test condition) the degree of metamerism is evaluated. [82] The measured (special) index of metamerism could be viewed as a test-illuminant-dependent value because the calculated colour differences are invariably contingent on the test illuminants chosen. [77] The spectral-based metamerism indices function as a single numerical value; many of them have been criticized for having poor correlation with visual evaluation. [83]

According to Roy S. Berns (2019):

"Having rank ordered the test conditions, a metameric index (MI) can be a weighted average of each colour difference, shown in Eq. (a) where w defines a weight and n is the specific illuminant. Another approach is to calculate the maximum colour difference, shown in Eq. (b). Any statistical metric can be used, such as the mean or a given percentile" [58]:

a) $$\mathrm{MI}_{\mathrm{weighted}} = \frac{\sum_n w_n \Delta E_{\mathrm{oo},n}}{\sum_n w_n}$$

b) $$\mathrm{MI}_{\mathrm{maximum}} = \max(\Delta E_{\mathrm{oo},n}) \quad (11)$$

An intriguing method is to structure the problem so that each illuminant is the reference illuminant, to compute a MI for each test condition using Eq. (b), and to perform the analysis. [58][60] utilise the formula with the minimum MI possible. [84] Illuminant metamerism is not evaluated using a standardised index. The performance of several indexes has been compared by Choudhury and Chatterjee (1996) [85] and Kuo and Luo (1996 a, b). [86]

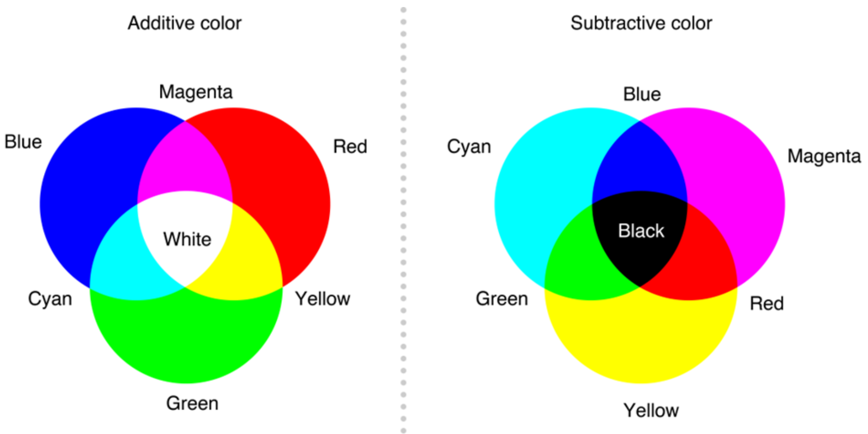
4. COLOUR MIXING

4.1 Additive and subtractive colour generation

There are two modes of colour generation that are important to distinguish and analyse; one of them is additive and subtractive colours generation. In daily life, for example, an additive colour model is used for television sets or flat panel display, where three primary colours red, green, and blue are added in different quantities to the colours generated.

This process produces the space of possible colours, called *gamut* of the display device. [87] When two colours, secondary colours are produced, such as mixing red and green produces yellow, or mixing red and blue the magenta colour is produced, and blue and green produce cyan. [30]

The combination of red, green, and blue creates white, where the secondary colour is created mixed with its opposite white, and the black colour is default colour as shown in (Figure 8).



a) Additive colours b) Subtractive colours

Figure 8. Arbitrarily utilised primary colours for a) additive colour mixing and secondary colours required for b) subtractive colour mixing [26]

Printing is a very important process where the subtractive colours model is used. A printed image or document only reflects the light that illuminates it, the light is absorbed, and the remainder is reflected. The colour of the point is determined by the light reflected by a point on the surface. [23] Deposited pigments that absorb one primary colour create colours.

In this case, the three primary subtractive colours are yellow, magenta, and cyan. From the yellow point blue is absorbed and red and green are reflected. Green is absorbed while red and blue reflect from the magenta point, red is absorbed and blue and green are reflected from the cyan point. If there is a combination of magenta and yellow, then green and blue are absorbed and only red remains. [87] Therefore, the combination of yellow and magenta creates red, the combination of yellow and cyan creates green, and by the combination of magenta and cyan, blue is created. Cyan absorbs red, while magenta absorbs green. In this way, red, green, and blue are secondary colours. The combination of blue, magenta, and yellow creates black, where it (black) is created also by the combination of secondary colour with its opposite. Therefore, white is the default colour. [87][88] It is often more challenging to forecast and quantitatively formulate the outcome of a subtractive mixture than an additive one. The challenge is brought about by the uncertainties surrounding dye interactions and the dependence of the mixture on many properties of the constituent materials, among them the size of particles, density, refractive index, and the transparency. [88] However, if paints have comparable tinting, opacity, and dilution, the reflectance value for paint or dye mixtures can be generally computed using the approximate geometric mean of the individual reflectance functions. [89]

The final combination can be relatively well predicted by employing a weighted geometric mean if the paints are not combined in exactly equal amounts. [90]

4.1.1 Specific characteristic of the colour

The main colour characteristics in a sense of view, distinction and description are hue, value and chroma. These specific terms are used to determine and distinguish a certain colour (CIE, 2011). [91] These characteristics are very appropriate processes, in terms of describing a certain colour, and all three are suitable for defining and using a colour for different purposes. [92] Hue is described using common colour names, for example, green, red, blue, yellow, so it distinguishes one colour from another. Value defines a colour how close to white or black, so by its darkness or lightness. [91] Finally, chroma expresses the purity of a colour. The synonym for the word's colours tone, shade, and tint is the word hue, but it is a dominant wavelength of light that a person can see, in terms of physics. [93] The difference between hue and colour is that colour is the term used to describe each variation of hue that can be seen, and hue specifically refers to the colours of the visual spectrum such as green, blue, red, orange, yellow, and violet. [91] On the other hand, the value is the term that refers to the brightness and darkness of the colour, that is, how close a colour to white is, the lighter it will be, and the darker it is, if it is closer to black. [92]

The value of the lighter colour is higher than the dark colour, so white has the highest value, and the black colour has the lowest value. Light, middle, and dark are values that have every colour. A pure hue can change lightness or darkness by adding black, white, or grey to a certain colour, and if we want to alter the colour, then it can be done with another colour. [91] The determination of a colour value is best done by a specific tool called greyscale. At one end there is black, and at the other end there is white, in the grey scale. The eleven-step value of this tool of black and white on both ends is divided into portions equal to 100%.

Let's focus on the two characteristics of colour hue and value. If the focus is on the purest version of each colour, it might be concluded that they are equal in value, but if the focus is away from the hue and look at the lightness, they do not have the same quantity values. [55]

The best example is yellow, considered lighter than any other colour, and blue and violet are darker than any other colour, as shown in (Figure 9).

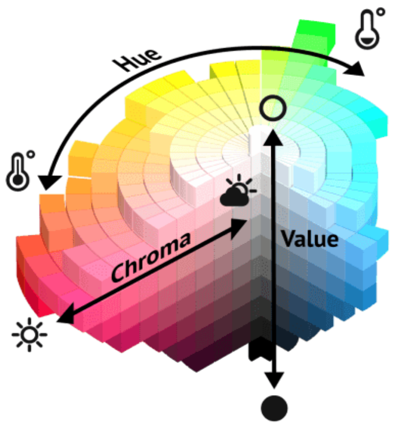


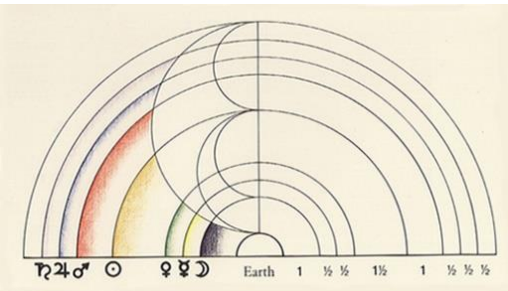
Figure 9. Specific characteristic of hue, value and chroma [198]

Chroma, as a very significant characteristic of colour, is the synonym of toned down, soft, muted, subtle, misty, dull that expresses the lightness or darkness of a colour with reference to how close it is to white or black. So, the main point for us, about these three characteristics of colour, is to remember the clear definition of three of them. Hue refers to the colour of a colour family, value determines the lightness or darkness of a colour, and chroma refers to the strength or intensity of a colour. [92]

4.1.2 The history of colours

The world and human evolution cannot be imagined without civilisation and colours. Objects distinction is made by colours, and by the psychological side, our concept about phenomena that surrounds us, is developed itself and changes our answer about this perception. In all historical perception, colour has drawn human attention, excited its curiosity, and always has been efforts for essentially discovering this mystery in all ancient civilisations. Colour was the subject of discussion, and different mythologies have been developed about it, even though these societies have not named many kinds of colour.

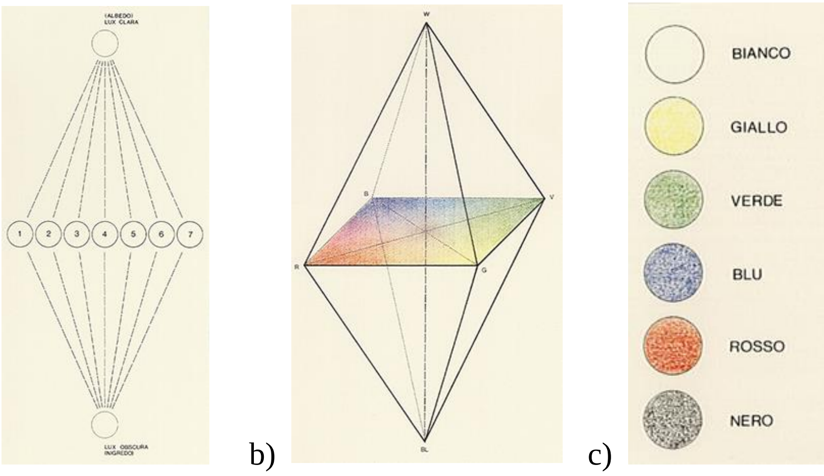
An explanation of the concept of *Pythagora*, which states that the placements of the planets between the earth and the sphere of the fixed stars, as well as the orderly arrangement of colours, provide the fundamental elements of all harmony. [94] Ancient philosopher *Aristotle* had considered that the black colour and white are the main real colours" that relate to life polarities: sun and moon, male and female, stimulation and calmness, extension, and shrinkage, outside and inside. As always, the philosophic perception of ancient Greece was the connection of colours with four elements: earth, water, air, and fire. [95]
Aristotle had seen the possibility of colour reflexion by changing the light during the day, "by this study, he created a linear system of colours that moved from the white of midday to the black of midnight", [96] [97] as shown in (Figure 10).

a) 

b) 

Figure 10. a) Pythagoras: colours are assigned to tones; b) Aristotle: Colours over the course of the day: white, yellow, red, violet, green, blue, black [97]

The first chancellor of the University of Oxford, *Robert Grosseteste*, in the early 13th century had a very fundamental and impractical interest in the phenomenon of colour. [98]
In the history of colours, this was the first circle of colours. [106] In his conception of the cosmos, which was based on the metaphysics of light, colour was intended to be the "prima materia" of the universe. [99][100]
Leon Battista Alberti, an Italian architect, and *Leonardo da Vinci*, an Italian painter, were more pragmatic in explaining the colours, as it shown in (Figure 11).



a) b) c)

Figure 11. a) Robert Grosseteste: 7 (nameless) basic colours between «Lux clara» and «Lux obscura»; b) Leon Batista Alberti: yellow, green, blue, red; c) Leonardo da Vinci: white, yellow, green, blue, red, black [199]

In the book "Della pittura" by *Leon Battista Alberti*, which was published in 1435, he managed to get by with four (real) colours that make up a rectangle on the panel: yellow (Giallo, G), green (Verde, V), blue (Blu, B), and red (Rosso, R). [101][102]
These four colours operate as the base for a double cone, whose tips are the achromatic extremes. The next goal for Alberti was to apply this development to create a functional method for stain mixing. He did not leave the readers with a visual picture of his ideas and just briefly discussed them in his book. [103][104]

The famous physician *Isaac Newton* had meticulously studied the physics of colours. Through sunlight reflected on the prism of glass, it is refracted in spectral colours. The spectral colours were the rainbow colours: red, orange, yellow, green, blue, indigo, and purple. [105]

According to Newton’s study, he approved that white light was the mixture of all spectral colours, illustrating the two-dimensional circle, [105][106] as shown in (Figure 12).

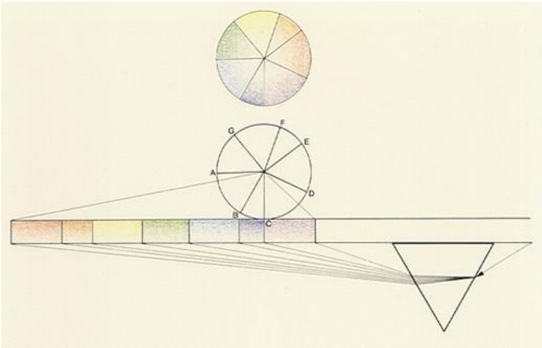
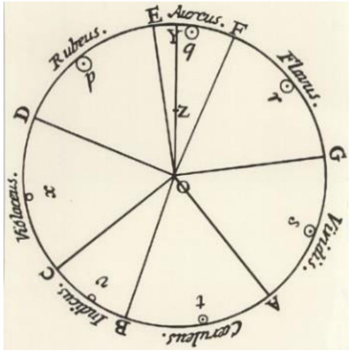
a)  b) 

Figure 12. The famous circular arrangement of the spectral colours of Isac Newton appears in 1704 in his central work on “Opticks” [199]

Considering that the experiment of Newton had to do with light, he didn`t manage to approve his discovery in a practical way by mixing the pigments, he had not been able, after the white is achieved, because the colours of pigments operate by subtractive dyes (colours). [107]

English graphist *Moses Harris* became well known in 1766. When he wrote his work Natural System of Colours. [104] [108] In this book, he presented three primary colours: red, yellow, and blue, which he called primitives. [109] According to Harris, the mixture of three primitive colours made the ‘complex’ colours or secondary one like: orange, green and purple, as it shown in (Figure 13). [108][109]

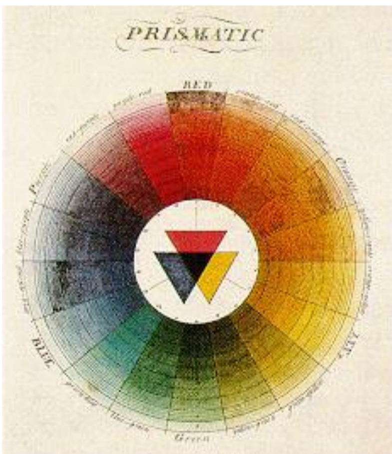


Figure 13. Moses Harris presentation of "Natural System of Colours", 1766 [109]

The second circle of colours from the book Natural System of Colours, published by Royal Academy of London about 1766, created his circle of 18 scales by three primary colours, colours approaching the centre, acquire darker tones of grey (Figure 13). [104][110][111]

In 1810, *Johan Wolfgang Goethe,* the German poet and scientist, published his book “The theory of colours”, which he called more important than his poetic creativity. In the history of colour theory, he was the one of the first modern intellects to interpret colours from the perspective of the human eye. [104][112]

All theorists, including Newton, too, were concerned more with the physics of colours, skipping the psychological factor of human perception. [104] Goethe opposed the physical theory of colours, and illustrating his theory, he presented a model on a two-dimensional circle based on a triad of primary colours such as red, yellow, and blue combined with secondary colours such as orange, green and purple placed as complementary to primary colours (Figure 14). [112]

His aim was to exceed Newton’s theory, by means of his research on the sensual and moral effects of colours. Besides the colour circle, he also presented the triangle, where he explained better the connection of colours. [113]

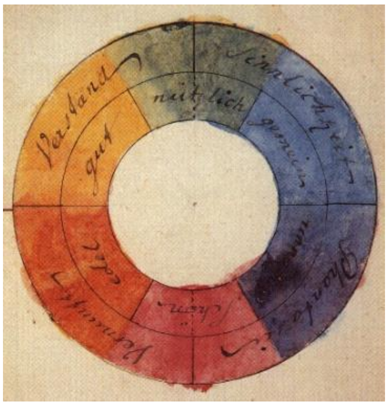


Figure 14. Goethe has been dealing with the problems of colour since 1791. His work "On Colour Theory" appeared in 1810 (the photo was taken personally from Goethe Museum in Dusseldorf, 2022)

‘Goethe explores all aspects of colours, such as the psychological and physiological reaction, the role of complementary colours, simulant contrast, successive contrast, shadow effects on objects, principles of proportional application of colours, etc.’ This extensive research into colours was introduced in his work that hadn`t been realised until then.[112] [113] [114]

The German painter *Philip Runge* in his work 'The colour sphere" published in 1810, presented the first historical model of three-dimensional colour (Figure 15), introducing twelve colours in the spherical format. [104][115]

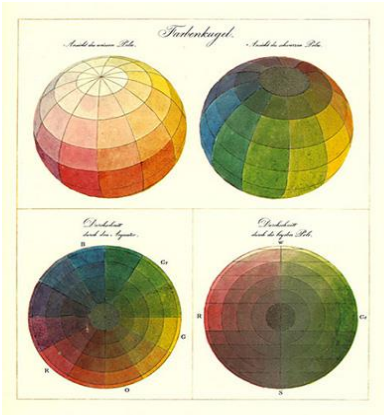
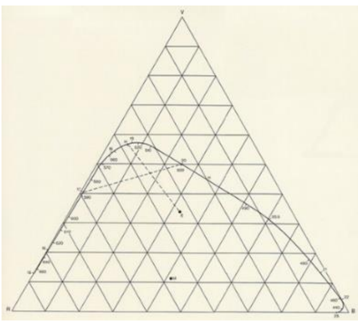


Figure 15. The painter Philip Runge in 1810 presented his construction of a sphere after working with colours for eight years [115]

The spherical model of Runge also had red, yellow, and blue as primary colours. However, nine other nuances were diffused to form the spherical equator. [116] [117] Each colour of Runge, had been mixed in two scales, black on one side of equator and the other white. [115]

Scottish physician and scientist *James Clerk Maxwell* (1831-1879), his experiments by the colour blending were revolutionary and brought the invention of colour photography techniques. [118] Maxwell experimented by combining additive or light colours. [119] [120]

He developed a colour diagram that had the form of a triangle (Figure 16), with the green, blue, and red displayed on the vertices of the triangle, the green on the blue, the purple on the yellow had placed on the side parts, then the white one was placed in the centre of triangle.

a) 

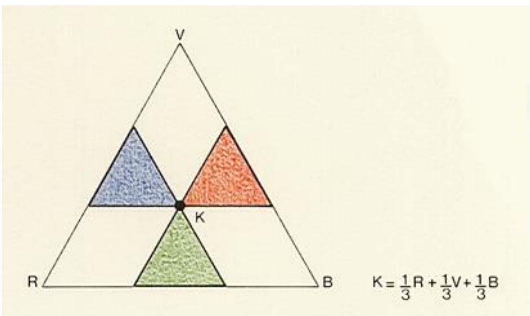
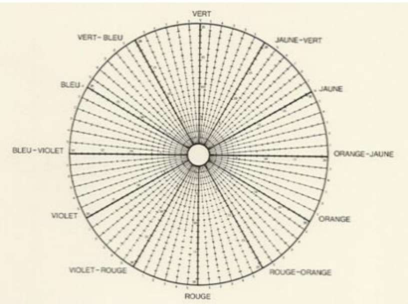
b) 

Figure 16. The physicist James Clerck Maxwell presented his theory of colour mixing between 1855 – 1860 [118]

In addition to his "theory of colour vision," which is regarded as the forerunner of quantitative colour measurement (colourimetry), the name of this scientist is still linked to four so-called field equations that were proposed to explain how light propagates and suggested the existence of electromagnetic waves, whose reception is used, for instance, by everyone in modern society when listening to the radio. [73][45][121]

Michel Eugene Chevreul, *French chemist*, had been appointed director of the famous Gobelin carpet manufacture in 1824, where he was a colour master. He approved that all colours can be obtained by blending the primary colours: red, yellow, and blue. In addition to the three main colours, Chevreul creates a 72-part colour wheel whose radius reflects three primary mixtures: orange, green, and violet, as well as six additional secondary mixtures. He noticed that certain colours placed in other colours would influence their layout. [104][122] This made him to start research of colours reaction. In the significant publication called 'The principles of colour harmony and contrasts', [122] he participated with his discoveries, where he made a great contribution in the discovery of the reaction that colours had with each other. Well-known principles of simulant contrast (based on complementary colours), successive colours (sequential), and optical blending, whereas the result of his research (Figure 17). [122][123]

a) 

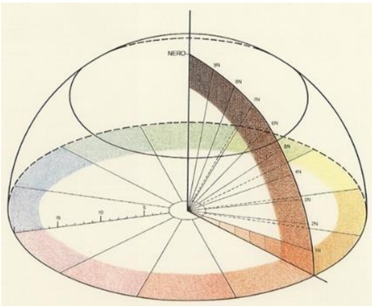
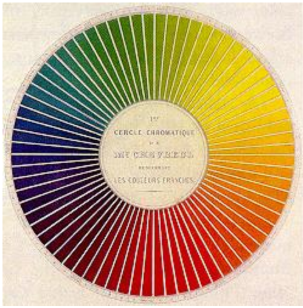
b) 
c) 

Figure 17. The 72-part colour wheel a), b), c) the chemist Michel Eugène Chevreul presented his (uncompleted) attempt at a systematic colour aesthetic in 1839 [199]

According to this research, Chevreul created his theory about the harmony of colours, about the combination of colours in art, in industry, and architecture that is still used nowadays as a certain standard in these fields. His works had a lot in the period of Impressionism in art. Artists of Impressionism and Neo impressionism affected Chevreul in his works. [104][124]

The American physicist *Nicholas Ogden Rood* was eminent by his higher education in science and art. This made him access to his intensive research for colours in these two aspects. [104]

In 1879, due to his long research Rood published his research and insights into physiological optics ‘Modern Chromatics’ as it shown in (Figure 18). In his work, he states that colours change because of three causes: purity (satiety), brightness (value and nuance). [125]
The main preoccupation was expressed in his research for optical mixture achieved through pointillism techniques. Small dots are not mixed with each other in this technique of painting but are placed next to each other to be visualised by the human eye, or in optical form. [125]

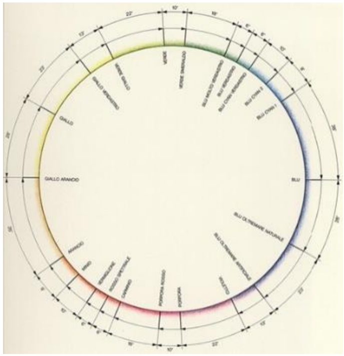


Figure 18. Colour wheel of Nicolas Odgen Rood presented his research and insights into physiological optics in 1879 [125]

By his circle Rod accentuated the significance of knowing complementary colours, to describe his theory, he based red, green, and blue as the primary colours. The colours of this circle or the complement of the cone were not achieved by mixing pigments but were achieved behind the images of the primary colours. According to his assertion, Rood accentuated those artists, based on his model, complement or directly behind the image of a colour, who would be able to create works still more powerful chromatic by this aspect. [125] [126]

The German physiologist and psychologist *Edward Herring* was deeply interested in colour perception theory. He considered red, yellow, blue, and green primary colours. Herring’s diagram is based on human perception, not on physical primary mixture. [104] This diagram was created in the form of a triangle, by pure colour, black and white placed on three sides of the triangle. The diagram of Wilhelm Ostwald and the Swedish system ‘Natural Colour System are based on Edward Herring. [127]

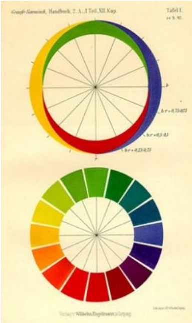
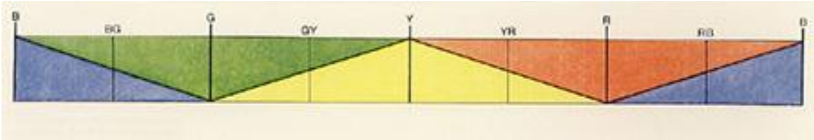
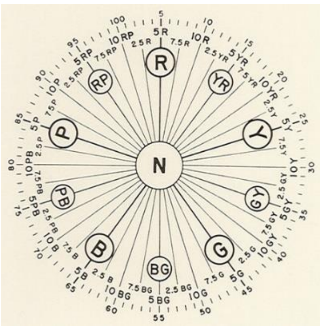
a)  b) 

Figure 19. The "Theory of the Sense of Light" by Edward Herring in Vienna in 1878, which opposed a purely physical understanding of colours [127]

The colour description was the first in history that was accepted and adopted as the official standard by the American theoretician *Albert Munsell* in 1905. He was based on Herman Helmholtzs theory, where the colour best is described by three variables: nuance (value), level of brightness (darkness), and chrome (satiety). [104] The Munsell system of colours is based on five primary colours, which he called them the principle one: red, yellow, blue, green, and purple. Behind the images of these five primary colours was created the basis of complementary colours. Munsell colour gave number 5 with the initials of the colour. For instance, the red colour is marked SR-Red. He gave an intermediate system of numbers, colours that were placed in the middle of five primary colours and five complementary colours. Number 5 marks the middle of each colour in this circle or system. If the marking 10R implies the colour between the values 5R and 5YR. In his system, the value of Munsell marked with number 0 to 9. According to this system, if it is marked 5R5 it presents the middle red colour, with the middle values. [128] [129] While higher numbers present a middle colour with middle values as shown in the photos below a) and b) as it shown in (Figure 20).

a) 

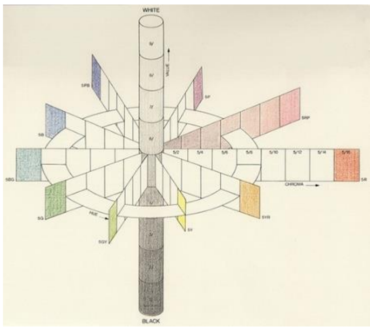
b) 

Figure 20. Colour systems by the American painter Albert Henry Munsell was developed between 1905 and 1916 [128]

Munsell's summarized system can be overviewed as follows: the first number and letter present the colour, the following second number presents the value, the third number presents chrome. This system of evaluation caused the revolution in colour marking, enabling artists to make accurate notes of colour components without proof. [129] In this way, in terms of a standard of colour evaluation for industries, this system enables precise specification of pigments. [130]

Wilhelm Ostwald (1953 - 1932), a German novelist for chemistry, was also a famous researcher of colours. He created his colour model based on geometric advancement.
In Ostwalds system, the degree of values is based on absorbing quality of colours. [131] [132] In arithmetic form, the initials 1,2,3,4, 5…, to each colour are added. Through this system, many gradual optic degrees were regarded as a colour evaluation. [133] [134] [135]
The achromatic degree of this system was 8 degrees, consisting of two triangles linked to one side, at a point of black colour, while in the other point of white colour (Figure 21). [136] [137] His system was based on three primary colours: yellow, red, and blue.

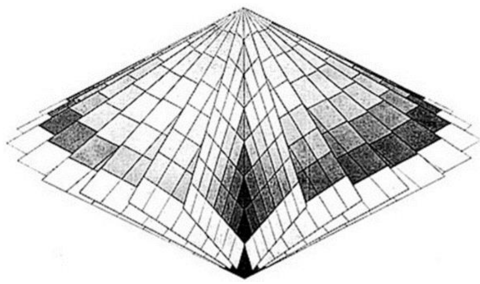


Figure 21. The colour system of Wilhelm Ostwald, a three-dimensional drawing [136]

According to his analysis of colour harmony, Ostwald considered that colours are the combination of corresponding nuances, with a percentage of black and white colour. [136]
All the mixtures were always 100%, that made them complete. [138][139][140][141]

Johanes Iten (1888-1967), Swiss professor of art, is the best known in colour theory with his antilogic work The Art of Colours. This work was also published with the title Elements of Colour. Iten was the lecturer about colour at the famous school Bauhaus. [104] Using the system of sphere and stars, he had made the description of colours (Figure 22). The star presented in a flat two-dimensional version was based on the earlier creator Otto Runge. [142] But Iten presented a yellow colour at the top of the star, because, according to him, that was the most visually approximate to the white colour, and it was the brightest of the other colours. [143]

Figure 22. Johhanes Itten Colour sphere in 7 light values and 12 tones, 1921 [142]

Alfred Hickethier, German painter (1903-1967) was the great researcher of colour reproduction in printing, especially in multi-engraving. After the previous study of the theory of colours, in 1952 he published the standardisation of printing colours. He created 1000 adjusted colours. This system was based on 3 printing colours, where the basic colour is yellow, magenta, and cyan. [104] The main purpose of Hickethier was the identification and description of the full range of printing colours. Through this system of primary colours and black colour, a number to each was given, while the white colour was described by 000 (the lack of colour), the black one by 999 (the presence of all colours), yellow by 900, magenta by 0.90 and cyan by number 009. [144][145] Consequently, he ranked the colours from yellow, magenta, to the end by cyan. The numbers and present colours in proportion should be mixed to form the other colours as shown in (Figure 23).

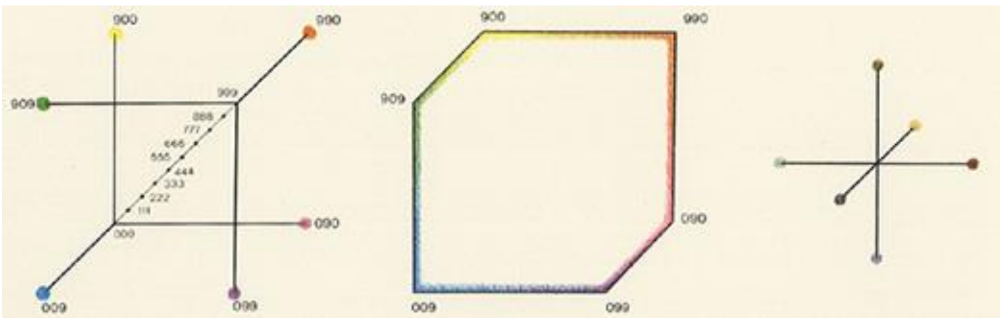


Figure 23. The Colour Cube of Alfred Hickethier was published in 1952 [144]

For the first time in history, this three-digit system enabled marking very bright colours that couldn't have been calculated earlier by the other systems. In this system, three primary colours were placed at the edges of the cube, presented in ten middle scales from 0 the lack of colour to 9 of its fullest intensity. Through this system very precise mixing was enabled to result in the very identical colour. [144][146]

The famous professor of colours, in Bauhaus school, *Josef Albers* (1888-1976), dedicated his career to colour interaction and reaction. In addition to his individual research on these phenomena, he encouraged the students to do their own research. [147]

Albers diagram in triangle form, used in his subject of colours, was like the one of Goethe, with red, yellow, and blue placed at the corners, and so the orange, purple and green at the three sides of the triangle. The red to grey, yellow to grey and the blue is to grey in the middle of triangle (Figure 24). Albers published his work Interaction of colours in 1963, because of his perennial research. [104][148][149]

Figure 24. Josef Albers production tests, printed paper, screen printing, offset lithograph, graphite ink with the notes 'Interaction of Color", 1963 [148]

Most of his research was focused on the simultaneous contrast effect. He also studied in detail the reactions near the edges of different colours during his career. In his studies, the rectilinear forms of placing the colours were used. According to him, this was used to provide research unlimited possibilities of colour combinations and the study of innumerable effects through presenting colours next to each other. [149]

Through thorough theoretician of colour *Faber Birren* (1900-1988) born in Chicago, during his sensational career, had managed to publish about 25 books with this topic, no doubt his work is appreciated as a colour expert and psychologist all around the world. Birren had made the difference between warm and cold colours. He created a circle 'rational colour wheel' with thirteen colour segments in a detached perimeter form the centre, proposed to allow more space for warm colours through the red and yellow colour than for cold one like that are between the green and purple. [150]

Since the human eye distinguishes warmer colours, in fact, they are more important in art. According to Birren, warm colours come from violet shortly before the red and extend beyond yellow. He specified that if a circle is constructed with the subtractive mixing of primary colours-yellow, blue, and red, parallel in space, the half of the circle would contain warm colours. Whereas if a colour circle is created with four primary colours of psychology and vision, yellow, green, blue, and red, the warm colours are pushed, and they are seen in less than half of the circle. [150][151]

With this system, Birren described the harmony and the practice of the artists. According to him, most of the artists give more meaning the warm colours than cold ones, because they are more dynamic and have an intensive effect. [151] The expression ‘Filling point’ refers to the fact that the circle of ordinary colours presents a grey colour to the eye when rotated around the centre, which would later be the mentioned filling point mentioned as it shown in (Figure 25). [151] Birrens colour circle doesn`t become grey after rotating around the centre. Birren in his theory formulated six types of harmony; elements of harmony, the one approached to harmony, harmonic opposition, harmony of triads, the harmony of the separated complementary, harmony of the dominant colours. [152]

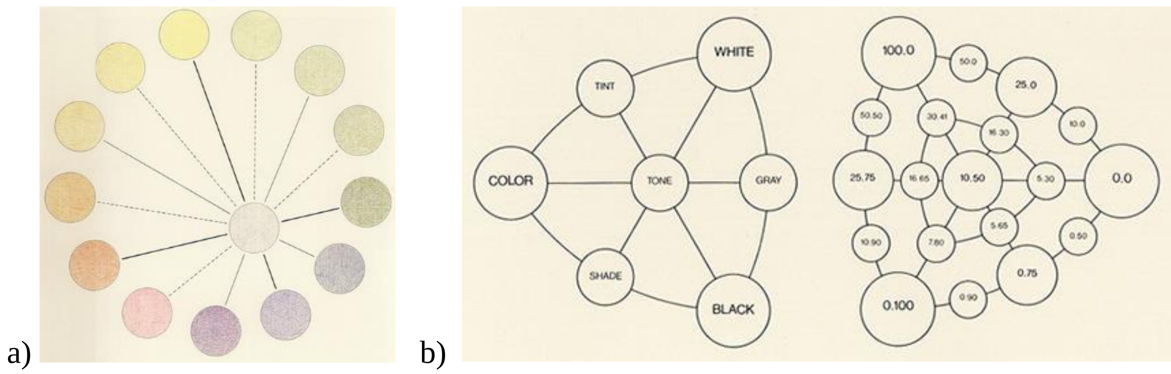


Figure 25. Faber Birren, the American art historian, designed his "rational colour wheel" in 1934 [199]

Working further on his system of colour harmony, Birren created the theory of re-perception of colours. From this theory, he specifies: the effect of iridescence, lustra effect, the effect of luminosity, the effect of transparency, and the effect of chromatic light. [152]

4.2 Artistic painting colour techniques

4.2.1 Tempera (Gouache) colour

Tempera (gouache) is a fluid, semi-transparent, opaque paint. It can either be painted on properly to create flat, matte opaque expanses of colour, or modified in semi-transparent washes like watercolour. It's standard practice when creating gouaches to overpaint in white and then add whiter to achieve hues. It can be painted over both coloured and white paper because it is opaque. [153][155] The word tempera comes from the verb temper that means ‘to bring to a desired consistency’. This kind of painting colour is executed with pigment ground in a water-miscible medium. Fresco paintings were distinguished by this kind of colour. Most of the world’s culture used tempera in ancient medium but was gradually superseded by oil painting in Europe. [154]

The ancient dynasties like Babylonia, Greece, Egypt, and China used tempera for mural medium, while the Christian catacombs were decorated with this kind of colour. The mixture with the yolk of fresh eggs was true tempera, but the white of eggs was often used by manuscript illuminators, where the whole egg was added by some easel painters.

Another mixture, the rich one, was egg yolk with gum and linseed oil, casein glue with linseed oil, and egg white with linseed.

Traditional tempera is a lengthy process. Being smooth surfaces, its supports contain planed wood, vellum, paper, stone, fine set plaster, and modern composition board of compressed wood or paper. [155] The 13^{th} and 14^{th} century were the times when the tempera was traditionally used by Duccio di Buoninsegna and Giotto, the flattened picture space of whom enriched by fields and textures of gold leaf, extended by the Renaissance depth perspectives in the paintings of many painters of this time. In that time oil painting was already used, being challenging to tempera painting. [154]

4.2.2 Oil colour

There are three things that create oil paint: the grinding pigment in oil, binder, and the thinner. Pigment refers to the colour element, whereas the binder (the oil) is the vehicle that holds the ground pigment to be applied to the paper, canvas or any other surface that is painted on. To apply with a brush, the viscous pigment-oil mixture. The oil paint dries by oxidation, reacts chemically with oxygen in the air, gradually changing from a liquid to a gel and finally becomes hard. [153][156]

The types of oil paint are linseed, safflower, poppy seed, or walnut oil. The most useful and popular of these types is linseed because it dries by oxidation, dries faster, and it can be easily re-worked in the process forms a more flexible paint film. Not all types of oil paint dry at the same speed. [153][157]

For centuries, drying oils had been used as binders for pigments to make paints, but around the 11th century it began to be applied, and in the 15th century the practise of easel painting with oil colour grows out. It is supposed that the Flemish artist Jan Van Eyck was the pioneer who painted “The Arnolfini Marriage” in 1434. He revolutionised the practise of oil painting, but he did not invent it. It is also supposed that the 11th century was the time of using this colour. The development of oil paint was recorded to be by Leonardo Da Vinci and Raphael, who used oil paint in combination with tempera.

Flexibility and the depth of colour are the main advantages of oil paint that are applied in different ways such as from thin glazes diluted with turpentine to dense thick impasto. This kind of colour allows the artists to create a greater richness of colour and a wide range of tonal transitions and shades. [153]

4.2.3 Watercolour

Watercolour paint is a fluid, versatile and widely used in variety of ways in painting, known for its transparent and luminous qualities. It is composed of pigments suspended in a water-soluble binder, usually gum Arabic. The binder in watercolour paint, gum Arabic, is derived from the sap of the Acacia tree. It acts as a dispersing agent, holding the pigment particles together and allowing them to adhere to the painting surface. Scientific studies have investigated the chemical composition and properties of gum, including its molecular structure, viscosity, and interaction with pigments. [158]

Gum Arabic has been used as a binder in watercolour paints for centuries due to its excellent solubility in water and ability to form stable suspensions.

Pigments used in watercolour paints can be organic or inorganic compounds, selected for their colour properties, lightfastness, and transparency. Historical watercolour pigments include natural earth pigments, such as ochres and sienna, as well as mineral pigments like ultramarine and vermilion. Modern synthetic pigments offer a wide range of colours and improved lightfastness. [153] The 18th century presents the time for applying watercolour by artists such as J.M.W Turner, John Constable, and David Cox.

They were the first artists who used the method of painting with this kind of colour. Due to size, these pigments can penetrate paper and cannot migrate very far. The density and their ability to sustain fibres are the features that differ pigments. [159]

4.2.4 Acryl colour

Compared with oil and watercolour painting that are long-standing, acrylic is medium.

Some of the important characteristics of acrylic colour is as follows: it is one of the least toxic colours, compared to other kinds of most flexible and versatile., water resistant, plastic polymer, so it is water-soluble. Dries quickly, so the artist can work in multiple successive layers without feeling cluttered, muddying the colours.

Acrylic colour can be used with water, being thinned, but if it is used too much water, then it will break down because little flecks will be left in the paint. Therefore, to avoid this, liquid acrylic in ink form is the best way to be used in painting. [153] Another characteristic of acrylic colour is that it is used like an oil colour, and because of its brightness colour.

This colour can be used in surfaces that are not too glossy and greasy, like: paper, canvas, brick, cloth, wood, masonite, concrete. [160] It was used for the first time by Diego River, one of the Mexican muralists of the 1920s, [and 1930s. He used this kind of colour with other muralists on a large scale because of its durability. Others, like in 1950, acrylic became available in a commercial aspect and its popularity has greatly increased since then. [161]

4.2.5 Pastel colour

Pastel paint is a unique and versatile medium known for its rich, vibrant colours and velvety texture. It is composed of pure powdered pigments mixed with a small amount of binder. The pigments used in pastel paint are finely ground, pure powdered pigments, often sourced from natural minerals or synthetic compounds. These pigments provide intense and lightfast colours. Scientific studies have examined the chemical composition and properties of various pigments used in pastels, including their colour characteristics, particle size distribution, and light fastness [153][158]. Understanding the properties of pigments helps artists select suitable colours and ensures the longevity of pastel artworks.

The binder used in pastel paint is a minimal amount of a neutral and non-greasy substance, such as gum tragacanthin or methyl cellulose. The binder acts as an adhesive, binding the pigment particles together and allowing them to adhere to the painting surface. [160]

The preparation of pastel paint involves mixing the powdered pigments with the binder to form a homogeneous mixture. This mixture is then shaped into sticks or pencils, allowing for easy application and control.

Artistic works that are done by pastel refers to those works that are covered in pastel, all over the painted surface. Their exquisite blend ability, their luscious texture, makes the work with the same depth and richness as paintings. In pastel drawings, we meet the surface, not all covered in pastel, because we can notice the paper or underlying surface showing through. These works are reminiscent of drawings and sketches. [160]

The importance of using pastel is based on its wonderfully luscious appearance of work, velvety texture, deep, rich colours, and ease of blend, for achieving splendid luminosity. There is no need to use a lot of tools to work with pastels, as would be with other paint colours. It is important to mention the disadvantages of using pastel; one of them is that the pastel particles are never fixed or set in place. [153]

5. COLOURIMETRY

The objective description of the physical correlates of colour perception is the subject of colourimetry. To provide an objective description of the colour at first, coloured samples were used. Physicists developed techniques for comparing coloured lights directly to reference lights. To improve the correlation between colour measurement and visual perception, many colour specification systems and colour differences have been proposed.

Modelling the human perception of colour is the aim of colourimetry that implies the following objectives. Colourimetry focuses on matching colours and predicting small colour differences when two stimuli are not matching. Colourimetric data alone do not specify what colour can be seen. [55]

Colourimetry is a field of colour science that specifies the numerical colour of a physically defined visual stimulus in such a way that: the specification should have the same effect when viewed under the same conditions, the certain numbers in the specification are continuous functions of the physical characteristics describing the spectrum radiant power distribution of the stimulus. [26][45][50]

5.1 Commission Internationale d'Eclairage -CIE

The International Commission of illumination or CIE in 1931, had begun more completed scientific standardisation of colour marking. Until now, the results of this standardisation of the system were more precise in measuring and marking the colour.

For the first time in CIE standard was used the instrument (colourimetry), through which the measuring of three colours variables had been made: luminance (the light intensity), nuance and saturation. All these three variables define the chromaticity of the colour. The more precise scientific way of describing the colour is provided by the CIE system, caused problems by fading printed samples of colour, and eliminated the incorrect interpretation of colours by humans. Although it is the most accurate in colour calculation, CIE diagram in the form of a horseshoe, it is not used in art. [45][50][162]

5.1.1 Tristimulus values

The CIE 1931 RGB colour specification system was created using the colour matching functions $\bar{r}(\lambda)$, $\bar{g}(\lambda)$, and $\bar{b}(\lambda)$, which were developed from two colour matching experiments (Guild, 1931; Wright, 1929). Monochromatic primaries for red, green, and blue were 700 nm, 546.1 nm, and 435.8 nm, respectively.

$$R = \int_{\lambda} \phi_{\lambda}(\lambda)\ \bar{r}(\lambda)\, d\lambda$$

$$G = \int_{\lambda} \phi_{\lambda}(\lambda)\, \bar{g}(\lambda)\, d\lambda$$

$$B = \int_{\lambda} \phi_{\lambda}(\lambda)\ \bar{b}(\lambda)\, d\lambda \tag{12}$$

where $\phi_{\lambda}(\lambda)$ the colour stimulus function is defined as the "description of a colour stimulus by the spectral concentration of a radiometric quantity, such as radiance or radiant power, as a function of wavelength" [163][50][26]

5.1.2 Standard Observer

The Standard Observer for Colorimetry was established in 1931 by the International Commission on Illumination (Commission Internationale d'Eclairage: CIE). A standard observer has been defined for the purpose of being used for accurate reproduction. Numerous industrial colour evaluation techniques are based on CIE colourimetry, and the fundamentals of this approach are still applicable today. [164]

5.1.3 Object colorimetry

Measurement of the colour of objects is the main issue in industrial colourimetry. Sun or a tungsten filament lamp as a source of radiant power emit the light striking the given object, making it visible to the observer. A sensation of colour identified as the colour of the object by the observer is the colour stimulus Q that emerges from the object and enters the observer's eye. [45][50]

The ASTM-D1729 standard practice for visual appraisal of colours and colour differences of diffusely illuminated opaque materials [165], this method describes the requirements for evaluating the colours and contrasts between colours of opaque specimens under diffuse illumination. The similar tristimulus values that are used for calculating chromaticity can also be utilised to evaluate an object's colour appearance. The colour stimulus function (also known as the colour signal) $\phi_\lambda(\lambda)$ is given by:

$$\phi(\lambda) = R(\lambda)\, S(\lambda) \tag{13}$$

where R(λ) is the spectral reflection factor of the object and S(λ) is the SPD of the light source consequently, it is possible to determine the CIE XYZ tristimulus values, [166]

$$X = k \int_\lambda R(\lambda)\, S(\lambda)\, \bar{x}(\lambda)\, d\lambda$$

$$Y = k \int_\lambda R(\lambda)\, S(\lambda)\, \bar{y}(\lambda)\, d\lambda$$

$$Z = k \int_\lambda R(\lambda)\, S(\lambda)\, \bar{z}(\lambda)\, d\lambda \tag{14}$$

where k is an adjustment factor,

$$k = \frac{100}{\int_\lambda S(\lambda)\, \bar{y}(\lambda) d\lambda} \tag{15}$$

so that Y = 100 for objects that perfectly reflect white (i.e., at each wavelength, all the light is reflected.) when R(λ) = 1 (CIE, 2004). [163] 'The Y value provides a basis for correlating the colorimetric calculations with the perceived hue chroma' [23][26]. So, for the Y value, it's shown as a percentage that can be anywhere from zero to 100. This doesn't apply to fluorescent objects. [163]

The definition of three-dimensional colour space by CIE has been considered more uniform than the CIE XYZ colour space. The intention for self-luminous colours is determined by the L*u*v* colour space. A range of approximately [- 100,100] is of the coordinates u' and u' as shown in formula below. The transformation of XYZ coordinates basically is done by the three-dimensional colour space, L* denotes luminance, i.e., radiance weighted by the spectral sensitivity function as it shown in below equation, [50][166]

$$L^* = \begin{cases} \left(\frac{29}{3}\right)^3 Y/Y_n, & Y/Y_n \leq \left(\frac{6}{29}\right)^3 \\ 116(Y/Y_n)^{1/3} - 16, & Y/Y_n > \left(\frac{6}{29}\right)^3 \end{cases}$$
$$u^* = 13L^* \cdot (u' - u'_n)$$
$$v^* = 13L^* \cdot (v' - v'_n) \quad (16)$$

The CIE L*a*b* color space is another approximately uniform colour space for perception as it was explained by International Commission on Illumination 1996. [50] This colour space was intended for use with surface colours, as it shown in (Figure 26),

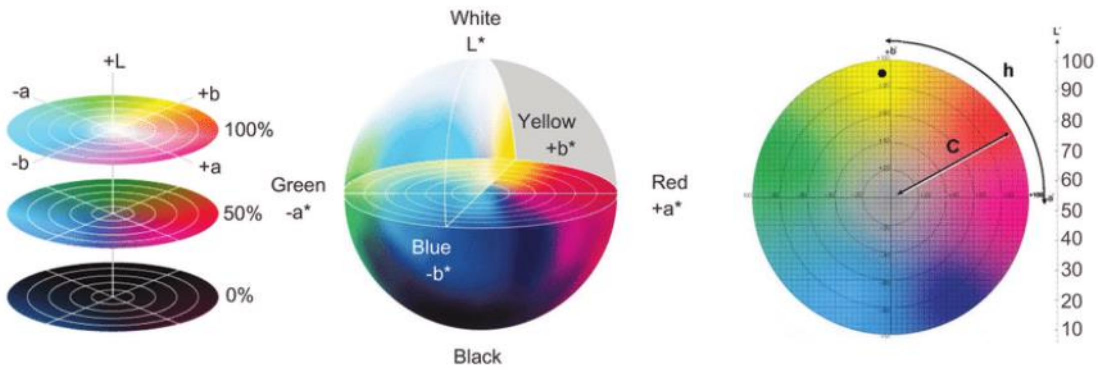


Figure 26. CIE L*a*b* and L*C*h* colour [200]

L* describes lightness and extends from 0 (black) to 100 (white). The a* coordinate represents the redness-greenness of the sample. The b* coordinate represents the yellowness – blueness. As shown in formula below the coordinates a and b have a range of approximately [-100,100]. [45][50]

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16 \quad \text{for } \frac{Y}{Y_n} > 0.008856,$$
$$= 903.3\left(\frac{Y}{Y_n}\right) \quad \text{for } \frac{Y}{Y_n} \leq 0.008856,$$
$$a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right],$$
$$b^* = 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right], \tag{17}$$

Despite the theoretical difficulty, the CIELAB space is found to be adequate in many practical applications. For viewing reflexion samples, the reference white can be taken as the reflection from a perfect reflecting diffuser under the same lighting illuminant. However, this is often unsatisfactory if the target is a photographic reflexion priand and our visual system makes some adjustment in its judgment regarding the "perceived" lightness depending on the illumination geometry in the scene.

The best density balance for typical reflexion prints also leaves some reflectance dynamic range to accommodate for specular highlights, so that they are printed 'brighter than white". Therefore, the common recommendation for the reference white in a reflexion print is to adjust the density to its scene- dependent optimum and then back-calculate what the ideal reflecting diffuser will be on that print and use that as the reference white. [45][163][166]

The CIELAB colour space and the first Delta E formula were two offerings from CIE in 1976. The measure of change in visual perception of two given colours is ΔE - (delta *E, dE*)

'Delta E is a metric to understand how the human eye perceives colour difference.

The term *delta* comes from mathematics, meaning change in a variable or function. [167]

The suffix *E* references the German word *Empfindung*, which broadly means 'sensation',

the CIEDE2000 colour difference was determined using the following simple mathematical overview. [167][168]

The explanation is identical to that of Luo, Cui, and Rigg with a little modification to make it more like an algorithmic explanation. It is reproduced here so that implementation recommendations and comments in subsequent sections can be related to the equations displayed below, the CIEDE2000 colour difference formula is based on the CIELAB colour space. [167][169][170]

It represents the CIEDE2000 colour difference between a pair of colour values in the CIELAB space, L*1, a*1, b*1 and L*2, a*2, b*2, as follows:

$$\Delta E_{00}(L^*_1, a^*_1, b^*_1; L^*_2, a^*_2, b^*_2) = \Delta E^{12}_{00} = \Delta E_{00} \tag{18}$$

The calculation of the colour difference is denoted by the following equations, which are organised into three basic parts, given two CIELAB colour values $\{L^*_i, a^*_i, b^*_i\}^2_{i=1}$ and the parametric weighting coefficients k_L, k_C, and k_H. [167][168][171]

Calculate C'_i, h'_i :

$$\Delta E^*_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C}\frac{\Delta H'}{k_H S_H}}$$

$$\Delta L' = L^*_2 - L^*_1$$
$$\bar{L} = \frac{L^*_1 + L^*_2}{2} \quad \bar{C} = \frac{C^*_1 + C^*_2}{2}$$
$$a'_1 = a^*_1 + \frac{a^*_1}{2}\left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right) \quad a'_2 = a^*_2 + \frac{a^*_2}{2}\left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right)$$
$$\bar{C}' = \frac{C'_1 + C'_2}{2} \text{ and } \Delta C' = C'_2 - C'_1 \quad \text{where } C'_1 = \sqrt{a'^2_1 + b^{*2}_1} \quad C'_2 = \sqrt{a'^2_2 + b^{*2}_2}$$
$$h'_1 = \operatorname{atan2}(b^*_1, a'_1) \mod 360°, \quad h'_2 = \operatorname{atan2}(b^*_2, a'_2) \mod 360°$$

$$\Delta h' = \begin{cases} h'_2 - h'_1 & |h'_1 - h'_2| \leq 180° \\ h'_2 - h'_1 + 360° & |h'_1 - h'_2| > 180°, h'_2 \leq h'_1 \\ h'_2 - h'_1 - 360° & |h'_1 - h'_2| > 180°, h'_2 > h'_1 \end{cases}$$

$$\Delta H' = 2\sqrt{C'_1 C'_2}\sin(\Delta h'/2), \quad \bar{H}' = \begin{cases} (h'_1 + h'_2 + 360°)/2 & |h'_1 - h'_2| > 180° \\ (h'_1 + h'_2)/2 & |h'_1 - h'_2| \leq 180° \end{cases}$$

$$T = 1 - 0.17\cos(\bar{H}' - 30°) + 0.24\cos(2\bar{H}') + 0.32\cos(3\bar{H}' + 6°) - 0.20\cos(4\bar{H}' - 63°)$$
$$S_L = 1 + \frac{0.015\left(\bar{L} - 50\right)^2}{\sqrt{20 + \left(\bar{L} - 50\right)^2}} \quad S_C = 1 + 0.045\bar{C}' \quad S_H = 1 + 0.015\bar{C}'T$$
$$R_T = -2\sqrt{\frac{\bar{C}'^7}{\bar{C}'^7 + 25^7}}\sin\left[60° \cdot \exp\left(-\left[\frac{\bar{H}' - 275°}{25°}\right]^2\right)\right] \tag{19}$$

5.1.4 Colour rendering index – CRI

Photography, where colour is important, such as museums, graphic design, printing, photography, and fashion, lighting for colour accuracy is crucial. Giving a constant and accurate depiction of colour under the employed light source is the main objective of lighting for colour accuracy. When choosing lighting for colour accuracy, several elements, such as the colour rendering index (CRI), Colour Temperature, and spectral power distribution (SPD), must be considered. [30][50] Colour rendering properties differ according to the relative spectral power distribution of the source; sodium lamps, which create nearly monochromatic light, perform very badly in this regard. With the introduction of fluorescent lighting, where the relative spectral power distribution could be adjusted at will across a significant range, it became highly useful to have a way of describing how well a specific source rendered colours. To do this, the CIE in 1965 established the General Colour Rendering Index, or R_a as:

$$R_a = 100 - \frac{4.6}{8}(d_1 + d_2 + d_3 + d_4 + d_5 + d_6 + d_7 + d_8) \tag{20}$$

where d1 is the distance between points in the u, v chromaticity diagram (multiplied by a factor of 800) that represent hues of the Munsell colour that have the same spectral reflectance. sources with correlated colour temperatures below 5000K; d2, d3, d4, d5, d6, d7, and d8 (instead of a D-illuminant, a Planckian radiator source is used). [30][26]

A true hue that appears from a light source is described by the colour rendering index (CRI) that is scaled from zero to 100. The best colour rendering properties is natural light which is 100. Depending on the intent of the space, CRI is critical.

A high CRI for the human eye to react favourably is needed for museums and retail works spaces; this must be 80-100 CRI. In comparison to a source of natural light, the CRI evaluates how well a light source reproduces the colours of things. A light source that properly renders colours and has a high CRI rating (above 90) is useful for colour-critical applications [172][173] as it shown in (Figure 27).

In interior spaces, there is colour consistency that should be evaluated in addition to CRI. Colour consistency in a museum is very significant for exhibits and the appearance of true colours. Under artificial light sources the materials and finishes will appear different. Reflective properties of the surface and context and the lamp colour spectrum are two things that colour rendition depends on. [174] The experience and expectations of an individual with normal vision are related to the context. The goal of museums is to educate viewers about the historical past and preserve artifacts. The correct use of colour and how lighting can impact that use of colour is included in the success of the museum lighting designs. [175]

Figure 27. Colour rendering index (CRI) and temperature [201]

5.1.5 Method for Evaluating Light ANSI/IES TM-30

The influence of a light source on the colour appearance of objects and surfaces, or as it is known as colour rendition, is a very significant part of lighting quality arising from the spectrum of the emitted light and that is reflected by surfaces and processed by the human visual system. The ANSI/IES TM-30 method combines scientific principles, colour science, and human perception studies to provide a comprehensive evaluation of light sources. It goes beyond traditional metrics, offering a more nuanced and accurate assessment of colour quality, which is valuable for applications where accurate colour rendering is crucial, such as architectural lighting, art galleries, and retail environments. TM-30-15 was published from the Illumination Engineering Society (IES) as a substitute for the CIE's CRI, because of advancements in colorimetry research and issues with the CRI. [176][26]

TM-30 became the American National Standard in 2018. [177] Dozens of lighting researchers have worked for decades to find details, where IES TM-30 was droughted by the Colour Metrics Task Group. In TM-30-15, average fidelity index (Rf), average gamut index (Rg), and a colour vector graphic (CVG) are used to measure changes in saturation and colour fidelity using a unified colour space. According to IES (2015), CVG shows changes in hue and saturation in an a *b * plot, with Rf ranging from 0 to 100 and Rg from 60 to 140 (when Rf >60). (IES, 2015). [178][179][26]

Some of the further improvements are specific to TM-30-15. These include the continuous reference illuminant (between 4500 K and 5500 K; the reference illuminant is conjunction of a Planckian radiator and sunshine), as well as a sizable collection of spectrally uniform colour samples that are equally sensitive to changes in the test SPD. Compared to earlier colour rendering metrics, TM-30-15 offers several of advancements. [179] CRI has existed for 50 years; it served a vital purpose and was recognised worldwide. [173][180][181]

However, two classes of deficiencies with CRI and broader 13.3 have been identified.

The first one, despite advances in colour, the underlying calculation framework never updated, and it relies on an accurate model of colour vision that is considered obsolete by the CIE. [173] Here is significant to emphasise a small set of colour samples that are not capable of capturing the full effect of a light source. [177][182][183] [184]

The second, the method CRI and the broader 13.3, only attempt to address colour fidelity, where the main deficiency here is not conveying how different colours change in appearance. These two deficiencies were an obstacle to the development and specification of more efficient and higher quality solid-state lighting devices. [177]

5.1.6 Accurate reproduction

Accurate printing or reproduction refers to the authentic and precise reproduction of colours, tones, details, and overall visual characteristics of an original image or artwork. It involves maintaining the integrity and authenticity of the original content throughout the printing process, ensuring that the printed output closely matches the intended or reference image. [185] Colour management requires a significant amount of uniformity in the desktop colour imaging environment of today, where different imaging peripherals can be converted out at will. [186] In this effort, the International Colour Consortium (ICC) has been quite active. This industry-driven group has developed a software framework to simplify the construction of well-managed colour-imaging systems. [187][188]

A key requirement for colour balance in reproduction is grey balance. A neutral will not be produced most often by the three printing process colour inks- cyan, magenta, and yellow, nor light neutral, medium, and dark greyscale at display values will be produced. Equal parts of red, green, and blue light are three colours that white light consist of. When all three are absorbed then the black is achieved in equal amounts, throughout the light range in the dark, and this ability of the process ink group is called grey balance. [65] In this way a very light grey would be produced by a value of 5% of the dots in each colour. An average value of grey would be produced by a value of 50% of the points in each of them. [77] Equal amounts of primary colours are not absorbed by equal process ink screens and thus a range of neutral grey values are not produced without correction. They are out of balance and imperfect. Bilevel halftones, often known as homogeneously thick and cleanly edged ink dots, are the default assumption in spectral prediction models for halftone prints. At the edges of the ink dots in actual prints, the ink thickness frequently lowers, creating continuous-level halftones as it shown in (Figure 28). [165][189]

Figure 28. Sample of grey balance field in reproduction printing

6. LIGHT IN MUSEUMS AND GALLERIES

6.1 Museum lighting

There are two main and very important issues to museum lightings: preserving artworks from damaging of light effects and provide the best visual impression to the visitors, through adequate light source. In many museums there are some principles of placing objects of artwork, according to their sensitivity to light and levels of luminance. But there is a very important issue about that, what source of light to use inside the museums to collide with the preservation of artworks and getting the best impressions to visitors at any time of the day. The development of technology, specifying here the lighting technology, enabled flexibility in some characteristics of lighting and setting such as luminance levels, correlated colour temperature and colour rendering properties.

All these characteristics have a significant impact on the visual impression of visitors. In the past decade, several studies have investigated the preferences and visual impressions of the observer about museum lighting. [190][26]

Based on light sources, LED is considered to have higher efficiency and better colour quality, including here naturalness. Undoubtedly, very important to be emphasised here is minimal infrared and ultraviolet radiation content. [16] What is characteristic for LED spotlights, they can change their chromaticity, they have small dimensions and can be less intrusive in exhibition spaces and change the visual appearance of artwork according to the intended effect. [58][26] Based on all these characteristics, LEDs are supposed to be very suitable and effective light source inside museums. LED, as a very potential and effective light source, has better impact in museum lighting compared with the traditional light source such as halogen, which can cause higher colour fade. [16][17] Many studies have focused on the lighting conditions under which the perception of painting was compared, with the aim of determining the best light arrangements. The focus has been on the CCT and the level of luminance. [190] The results showed that the artwork under illuminance of approximately 3600 is preferred by the observers because they considered that arrangements were neither too cool nor too warm.

6.1.2 Effects of lluminant Metamerism on artistic paintings

It is especially important to mention that not all light is the same since different temperatures derive from different light sources, this is because under the warm light of a sunset colours will look different compared to the cool light of an overcast day. According to research and experiments there are supposed to be two steps to use correct painting the light. The first step is to choose the correct light that illuminates the painted subject, where it would be the easiest way to use certain points. This is because of the fact yellow and red are always warm, light, and bluish - white is always cool. [191]

The dominant light source is warm if a sunset is painted, and dominant light source will be cool bluish white. But it is not as simple considering that nature is unforeseeable and reflects light. There are cases where there is no certain point that it can be referred to because the light sometimes is so neutral that it cannot be specified if it is warm or cool.

Therefore, it is necessary to consider the observation so that the colour of the light source can be identified. [77] It is especially useful to have the instruction like cool light, warm shadow, warm light cool shadow. If the appearance of shadow is warm compared to the light areas, then it is supposed that the light source is cool, and vice versa if the appearance of shadow is cool compared to the light areas, then the light source is warm. If the primary colour of the light is determined precisely, it is required using the colours that line up with that light source. Under certain light there are certain colours that cannot exist; for instance, the red object under the blue light is closest to the black whereas the vivid cadmium used on scene in blue light would be inappropriate. [191]

If the light is warm, cool colours must be restricted (such as blue) and warm colours will retain saturation. If the light is cool -warm colours must be restricted (such as orange and red) and cool colours will retain saturation. As it is said, the colour temperature of sunset is very warm and inclines toward orange, so in case of painting the sunset, then it would be no sense having strong blue under that light.

An object with a blue colour (like the blue of sea) under warm light, is closer to grey than a rich blue; the stronger the light would be, and the blue colour is less blue. The colours seen in the shadow would be cooler than colour in light, based on the warm light cool shadow instruction. Using strong blues and purples in the shadows, the sense of temperature contrast is already given. Lighting significantly affects the protection of artistic works, and its proper use is crucial for preserving the integrity and longevity of the artworks. [191] The impact of lighting can vary depending on the type of artwork and the specific period it belongs to.

Here are some considerations for using lighting in relation to different periods of paintings: Pre-modern and Renaissance Periods: Paintings from these periods often utilize traditional materials such as tempera or oil paints. They tend to be more robust and less sensitive to light.

However, it is still important to avoid excessive light exposure, as it can cause fading and discoloration over time. It is recommended to use moderate and controlled lighting conditions to ensure the protection of these artworks. Baroque and Rococo Periods: Paintings from the Baroque and Rococo periods may incorporate delicate materials and intricate details.

They often feature vibrant colours and subtle tonal variations. To preserve these artworks, it is essential to use lighting that enhances the nuances and details without causing any harm.

The use of adjustable spotlights or focused lighting can help bring out the richness of colours while minimizing potential damage. Impressionist and Post-Impressionist Periods: Artists from these periods, such as Monet, Renoir, and Van Gogh, employed techniques that captured light and its transient effects. The choice of lighting for displaying these artworks is crucial to convey the intended luminosity and atmospheric qualities. [193]

It is recommended to use diffused and controlled lighting, avoiding direct beams that could create glare or uneven lighting conditions. Modern and Contemporary Periods: Artworks from the modern and contemporary periods encompass a wide range of styles, materials, and mediums. These artworks often involve experimental techniques and unconventional materials. The lighting approach should be tailored to each artwork's specific requirements, considering the artist's intentions, the materials used, and any special display considerations.

Collaboration with conservation experts and lighting specialists can help determine the most suitable lighting techniques for these artworks. In all periods, it is important to consider the duration of light exposure. To minimize the risk of damage, artworks should not be subjected to excessive lighting for extended periods.

Additionally, the use of UV filters and controlled lighting with appropriate intensity and spectrum can help protect artworks from fading, discoloration, and other light-induced deterioration. Ultimately, the selection and application of lighting for artworks should be done in consultation with experts in conservation, curators, and lighting specialists. By carefully considering the characteristics of the artworks and their respective periods, it is possible to strike a balance between optimal display conditions and the long-term preservation of these valuable artistic treasures. [191]

In a further investigation, the light source spectrum was modified using several filters to keep the illumination incident on the artworks while preventing colorants from fading. [194][26]
In a further investigation, the light source spectrum was modified using several filters to keep the illumination incident on the artworks while preventing colorants from fading. [194][26]
Professor Janos Schanda, who was part of this university, introduced the idea of a major project for quality lighting in the Sistine Chapel. The lighting measurements and fresco analysis were conducted by Prof. Ferenc Szabo, from the same faculty. To achieve this major project and serious work, aiming to achieve the realisation of the natural lighting as Michelangelo saw it at that time, to offer visitors the same experience as during the creation of the artworks, it required a team of expert workers and various measurements to achieve this result. The lighting used in the Sistine Chapel is Led light - Osram. Various tests were performed, including quality management and colour testing, at one of the most visited places in the world. The Sistine Chapel changed its illuminant and is now using 7,000 Osram LED lights to mimic natural light and protect the frescoes from further fading. [195]

7. EXPERIMENTAL PART

7.1 Research plan

The experimental part of this research started by doing five similar paintings, in different painting techniques, in a way of different techniques that contain necessary elements for subjective and objective identification of painting qualification, under illuminant metamerism. The form of painting will consist of painting techniques with tempera (gouache) colour, oil, acryl, water, and pastel. These paintings with similar symbolic elements present the elements that define them on the visual presentation, using illuminant metamerism. Painting work has been done with three subtractive colours: red, yellow, and blue. The works were done on the paper of 300gr mat paper in 320x420 mm, because such format was more suitable for technical comparison and more accepted by the observers in the nearest space.

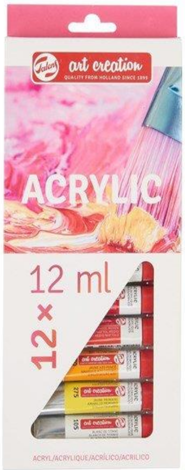
To be analysed, the visual perception of painting under the illuminant metamerism, printed samples with grey balance field have been selected, where the fields in the printed form were established, to control the increasing and decreasing on reduction of density. Spaces of grey balance field with values (C 50%, M 40%, Y40%) have been added to these images. To achieve to these printed samples, the original paintings have been photographed in a professional way by the Canon camera EOS 5DS R, by manual objective of lighting, in standardised condition, this has done to get more qualitative photography.

Worked samples for the comparison to the most similar with the original paintings were processed by Adobe photoshop 2020 programme, changing the tonality of colours CMYK, increasing and decreasing the half tone colour in a very small percentage from 50% starting point, by values +/- 2%, 4%, 6%. The level of curves change of colours will be divided in each colour in rise, such as Cyan, Magenta, Yellow, and +Cmyk and -Cmyk in reduction of colours. Colours at equal intervals and areas of range control will be defined near these areas. Achieving this tonality over the image in objective aspect, samples have been measured in the grey space, because of the inability of measuring in another space, considering that the images would be analysed completely and not at a single certain point. To set colorimetric values of printing in a part of grey level, in the printing form, there have also been spaces to control the space of this colour. In addition to the listed fields that can be used to perform the objective control of the

printing quality of colours, in the printed form, printing samples of different tonalities were analysed, which were useful to evaluate the subjective quality of the standard observer.
The experimental part has been carried out in a laboratory atelier with a a space of 4 x 4 m2 = 16 m2 with light grey interior of the walls, where the lightning will be placed on the widest wall of laboratory space above the paintings. Considering that the main part of this research is illuminant metamerism, which in this research include five different sorts of light source, like LED light 3000K, 4000K, 6500K, Wolfram light, and Halogen light. Each painting was analysed under five different light sources. Standard observers were asked to select five samples that were most like original paintings. The chosen samples will be classified by point, from the best one of five points and the smallest similar one by 1 point.
This will enable visual and classification and suitability.

7.1.1 Objective research

The used colour techniques were chosen by the company Royal Talens – Art Creation, and their history dates from 1899. Since it is an old product and has expanded with the artistic world, its quality has been considered in the foreground in the various products of colours. In this research five colour techniques were chosen: Acrylic, Oil, Tempera (Gouache), Watercolour, and Pastel. The colours chosen in these paintings are used only primary pigments as: blue, red, yellow, as it shows below in the (Figures 29, 30, 31, 32, 33), to correlate with the colours of the lighting and the vision of the observers, where observers can find adaptability and ease of identification between them.
Colour names and numbers that are used are coloured blue, in the specifications below.
The motive of the paintings of different colour techniques is the same as being able to compare them. The paintings were done individually, under the same conditions and with standardised lighting.

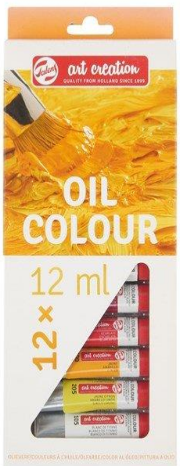


TALENS ART CREATION

9021712M

Contents: 12 x 12 ml tubes (105 Titanium White – 227 Yellow Ochre – 270 Azo Yellow Deep – 275 Primary Yellow – 369 Primary Magenta – 396 Naphthol Red Medium – 409 Burnt Umber – 411 Burnt Sienna – 504 – Ultramarine – 572 Primary Cyan – 619 Permanent Green Deep – 701 Ivory Black). [196]

Figure 29. Acrylic colour set, pigment used (275 Primary Yellow – 369 Primary Magenta - 572 Primary Cyan [202]



TALENS ART CREATION

9020112M

Contents: 12 x 12 ml tubes (105 Titanium White – 205 Lemon Yellow (Primary) – 200 Yellow – 334 Scarlet – 318 Carmine – 504 Ultramarine – 530 Sèvres Blue – 662 Permanent Green – 227 Yellow Ochre – 411 Burnt Sienna – 409 Burnt Umber – 701 Ivory Black).

Figure 30. Oil colour set, pigment used (200 Yellow – 334 Scarlet – 504 Ultramarine) [202]

TALENS ART CREATION

9021612M

Contents: 12 x 12 ml tubes (100 white - 205 Lemon Yellow (Primary) – 201 light yellow - 334 Scarlet – 362 Deep Rose – 512 cobalt blue (ultramarine) - 501 Light Blue (Cyan) – 602 deep green - 227 Yellow Ochre – 411 Burnt Sienna – 409 burnt umber - 700 Black).

Figure 31. Tempera (Gouache) set, pigment used (205 Lemon Yellow (Primary) - 362 Deep Rose - 501 Light Blue (Cyan) [202]

TALENS ART CREATION

9022012M

Contents: 12 x 12 ml tubes (108 Chinese White – 200 Yellow – 334 Scarlet – 326 Alizarin Crimson – 504 Ultramarine – 535 Cerulean Blue (Phthalo) – 617 Yellowish Green – 602 Deep Green – 227 Yellow Ochre – 411 Burnt Sienna – 409 Burnt Umber – 708 Payne's Grey).

Figure 32. Water colour set, pigment used (200Yellow – 326 Alizarin Crimson – 504 Ultramarine) [202]

TALENS ART CREATION

9029012M

Contents: 12 pastels (100 white - 200 Yellow – 202 Deep Yellow – 398 Naphthol red light - 318 Carmine – 570 Phthalo blue - 535 Cerulean Blue (Phthalo) – 617 yellowish green - 615 Emerald Green – 227 Yellow Ochre – 408 raw umber - 700 Black).

Figure 33. Soft pastel set, pigment used (200 Yellow - 398 Naphthol red light - 570 Phthalo blue) [202]

The paintings are made in Italian matte Fabriano I264 paper long life ISO 9706 (Figure 34), since reproduction on paper is used, this type of Mix media paper was chosen, colour and composition 100% alpha cellulose, surface and finishing- natural grain, grammage 300gsm, which is suitable for all techniques and easier to compare with the reproduced samples.

Figure 34. Mixed media paper used for different colour paintings [203]

7.1.2 Applied devices

In the experimental part of the work, a Canon EOS 5DS R digital camera was used to record the original paintings (Figure 35). At this stage, the research continued with the photography of the original works in natural lighting, with manual white balance. Since this, it affects the way balance is adjusted.

This process played a very important role in the ongoing processes, the comparison with the original paintings, and the presentation of the samples in the press.

Figure 35. Recording of the original paintings with Canon EOS 5DS R [204]

The specific data on the technical characteristics of the Canon EOS 5DS R digital camera for the tool used to photograph original paintings (Table 1).

Table 1. Technical characteristics of the Canon EOS 5DS R digital camera

Body type	Mid-size SLR
Max resolution	8688 x 5792
Effective pixels	51 megapixels
Sensor size	Full frame (36 x 24 mm)
Sensor type	CMOS
ISO	Auto, 100-6400 (expandable to 50-12800)
Lens mount	Canon EF
Focal length mult.	1×
Articulated LCD	Fixed
Screen size	3.2″
Screen dots	1,040,000
Max shutter speed	1/8000 sec
Format	H.264
Storage types	SD/SDHC/SDXC (UHS-I compatible), CompactFlash
USB	USB 3.0 (5 GBit/sec)
Weight (inc. batteries)	930 g (2.05 lb / 32.80 oz)
Dimensions	152 x 116 x 76 mm (5.98 x 4.57 x 2.99″)
GPS	None

7.1.3 Recording and processing of test samples

In contrast to traditional photographic systems, the digital ones (Figure 36), started recording, which illuminates the photosensitive media sensor, and the resulting picture was recorded as a digital record on a storage medium, in the memory card. The digital record was processed properly applied in the manual shot and ready for quality printing, replicated on the screen. In the experimental research study, the procedure of the material processing methodology and scaling of the working stages have been followed before being presented to the observers.

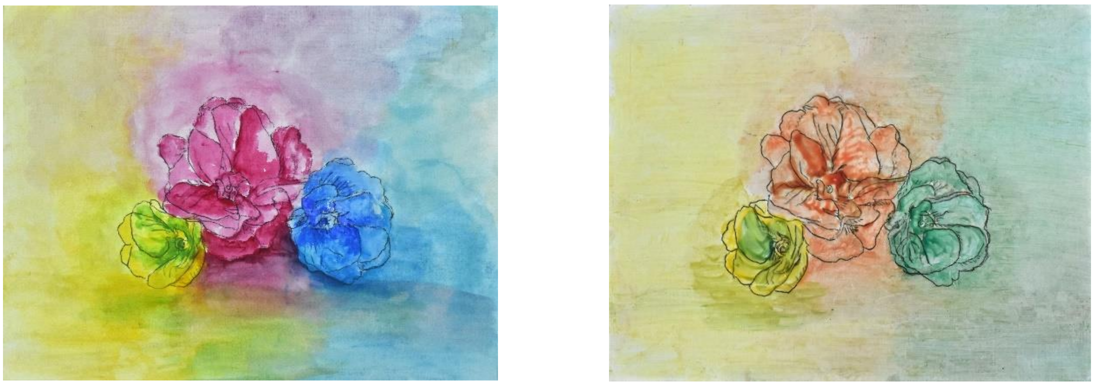
The first stage is done with a similar motif of five different colour techniques such as: Tempera (Guache), oil, acrylonitrile, pastel, water. These five paintings were created under the same standardised conditions. As a second phase, five paintings of different techniques were taken and photographed with a Canon camera in manual natural light so that the necessary values could be determined.

In the third phase, the digitised photos were taken from the storage medium and transferred to a computer, where they were presented Image display on the screen. In the fourth stage, due to printing and technical issues, all digitised photos of the original paintings were placed in the digital process in the Adobe Photoshop 2020 program, where a grey balance field was placed in the left corner of the painting with the same values. In this program colour correction of all images in all divisions of CMYK colour space in tonal difference from the average line, with increasing and decreasing values of 2%, 4%, 6% / -2%, -4%, -6%.

In the fifth stage, the samples are transferred with storage memory to the monitor to be reviewed in the pre-print stage. Also, before printing, the monitor is calibrated. In the sixth stage, the samples were printed on a calibrated printer Xerox colour c70 in high quality, to achieve the most accurate samples. In the seventh stage, after the selection of the observers of the most similar samples. Measurements of the L*a*b* values were made with Exact spectrophotometer, to objectively analyse the study part.

Figure 36. The scheme of the experimental research process

The selected photographs most similar to the original have been repeated until the most pleasing and similar results are achieved, in order to have the opportunity to continue the study further (Figure 37).



a) Acryl painting b) Oil painting

c) Tempera painting

d) Water painting

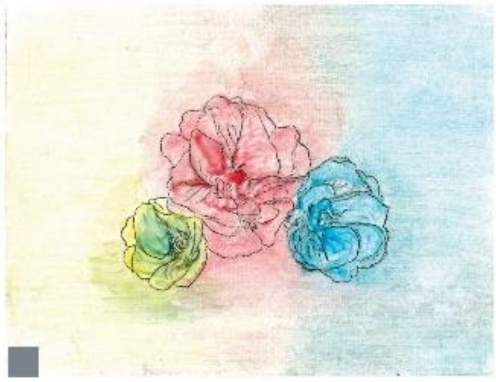
e) Pastel painting

Figure 37. Recording of five different painting techniques

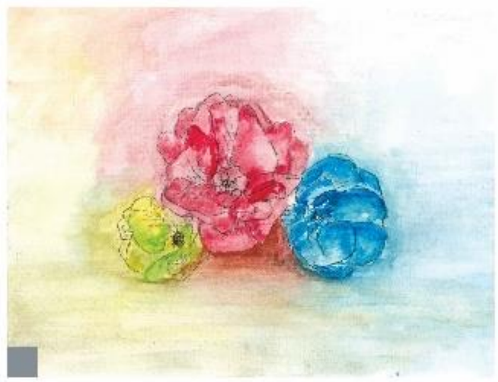
Digital records taken from photographic images were downloaded on the Adobe Photoshop 2020 programme, with perceptive interpretation in the CMYK reproductive colours CMYK. For technique reasons and more precisely, five photographic images of different techniques were placed into the programme site, being enabled to function parallel, equally in the changing of curves. In the second phase, all photographic images were placed in a cube-grey balance field (Figure 38), where the accurate dimensions were determined according to standardization (50% C, 40% M, 40% Y). This cube enables accurate measurement of half-tone change of whole image, being unnecessary to measure the parts. In this space colours have been separated, starting from average value 50% of CMYK colour space on half colour tone images by increasing and decreasing +/-2%,4%,6%, the tones have been changed to three certain percentages, and this has been continued the same for Cyan, Yellow, Magenta, +CMYK and -

CMYK. The last one has sample values such as -48%, -46%, -44%. This was achieved from each painting technique of 15 samples for each in different half-colour images.

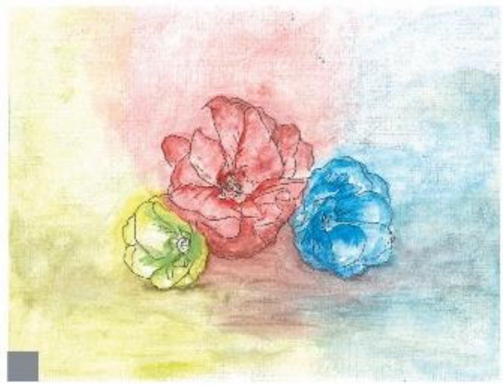
a) Acryl sample



b) Oil sample



c) Tempera sample



d) Water sample

e) Pastel sample

Figure 38. Photographic images with cube-grey balance field

All of them have been saved on the JPEG record of the highest clarity.

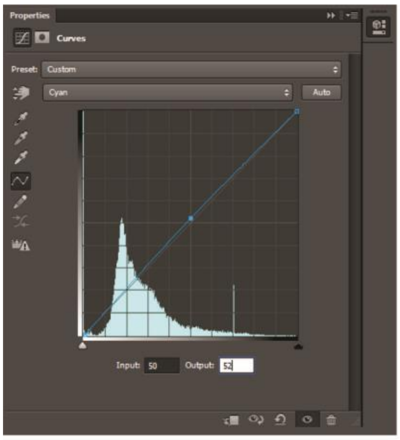
The names of the initial testing samples are included in (Table 2), and they were shortly utilised as a key letter to identify which tonality and percentage of halftone images were discussed in the research.

Table 2. Initial testing samples and percentage of increased and decreased halftone image values from the CMYK colour space

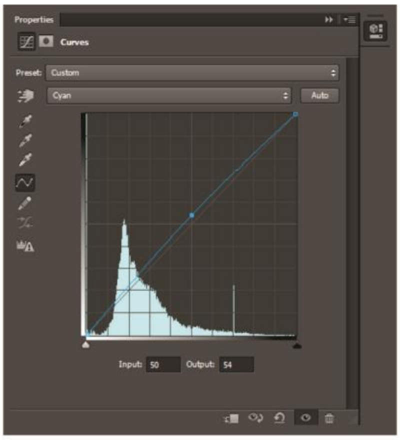
Percentage of increased and decreased halftone image values from CMYK color space	Sample initials
52% Cyan	2% C
54% Cyan	4% C
56% Cyan	6% C
52% Magenta	2% M
54% Magenta	4% M
56% Magenta	6% M
52% Yellow	2% Y
54% Yellow	4% Y
56% Yellow	6% Y
52% CMYK	2% K
54% CMYK	4% K
56% CMYK	6% K
-48% -CMYK - Lighter	-2% L
-46% -CMYK -Lighter	-4% L
-44% -CMYK -Lighter	-6% L

Tonality changes in the CMYK colour space division were made with the properties option, and through the curve’s histogram the x, y axis options were available. Due to the small tonal difference and the small subjective difference, only the output movement on the x axis is selected. In this space colours have been separated, starting from average value 50% of CMYK colour space on half colour tone images by increasing and decreasing +/-2%,4%,6%, the tones have been changed to three certain percentages on the x axis of output, and this has been continued same for Cyan, Yellow, Magenta, +CMYK and -CMYK.

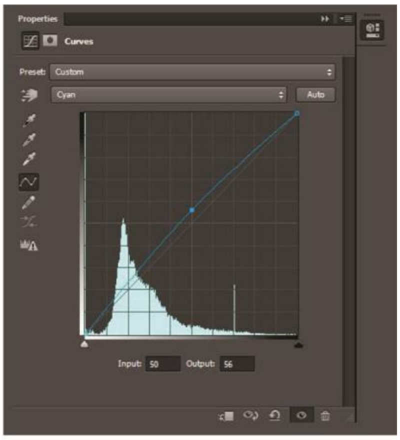
The last one has sample values such as -48%, -46%, -44%. This was achieved from each painting technique of 15 samples, each in different tones (Figure 39). All of them have been saved on JPEG records of the highest quality.



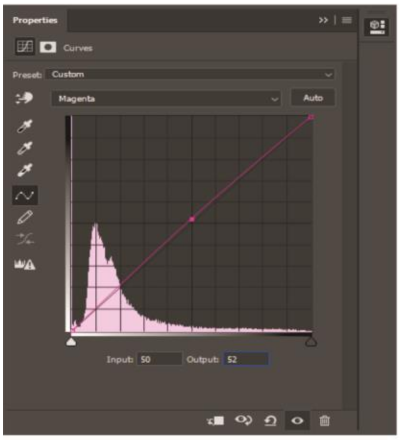
2% C



4% C

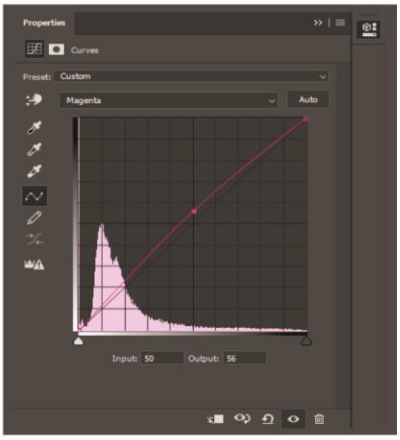


6% C



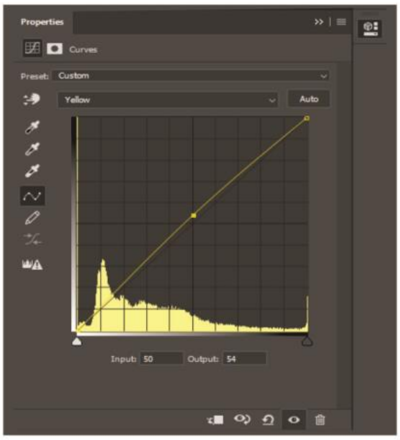
2% M

4% M

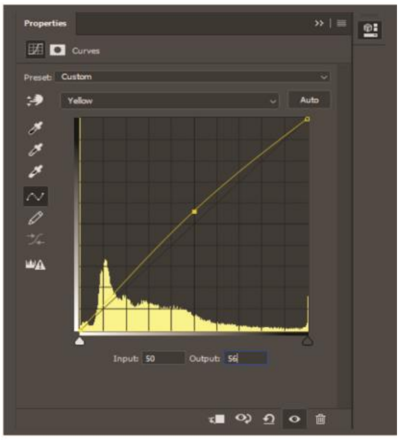


6% M

2% Y



4% Y



6% Y

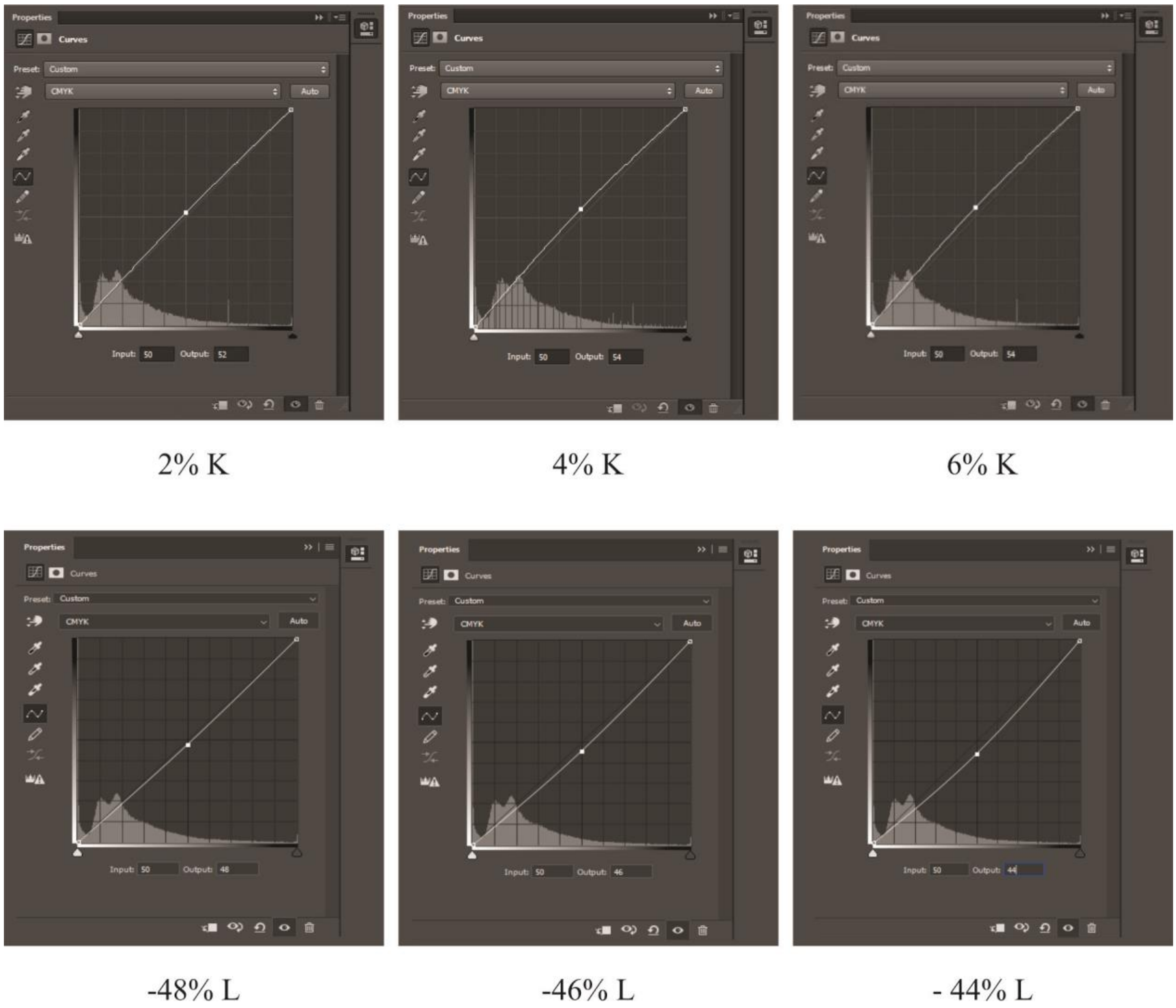


Figure 39. Histograms of changing half-tone colour image in CMYK space colour

Subjective changes of 15 samples of image reproduction of images on the Tempera (Guache) colour technique with increasing and decreasing values, finding similarity and comparison with the original painting under different light sources through visual perception (Figure 40).

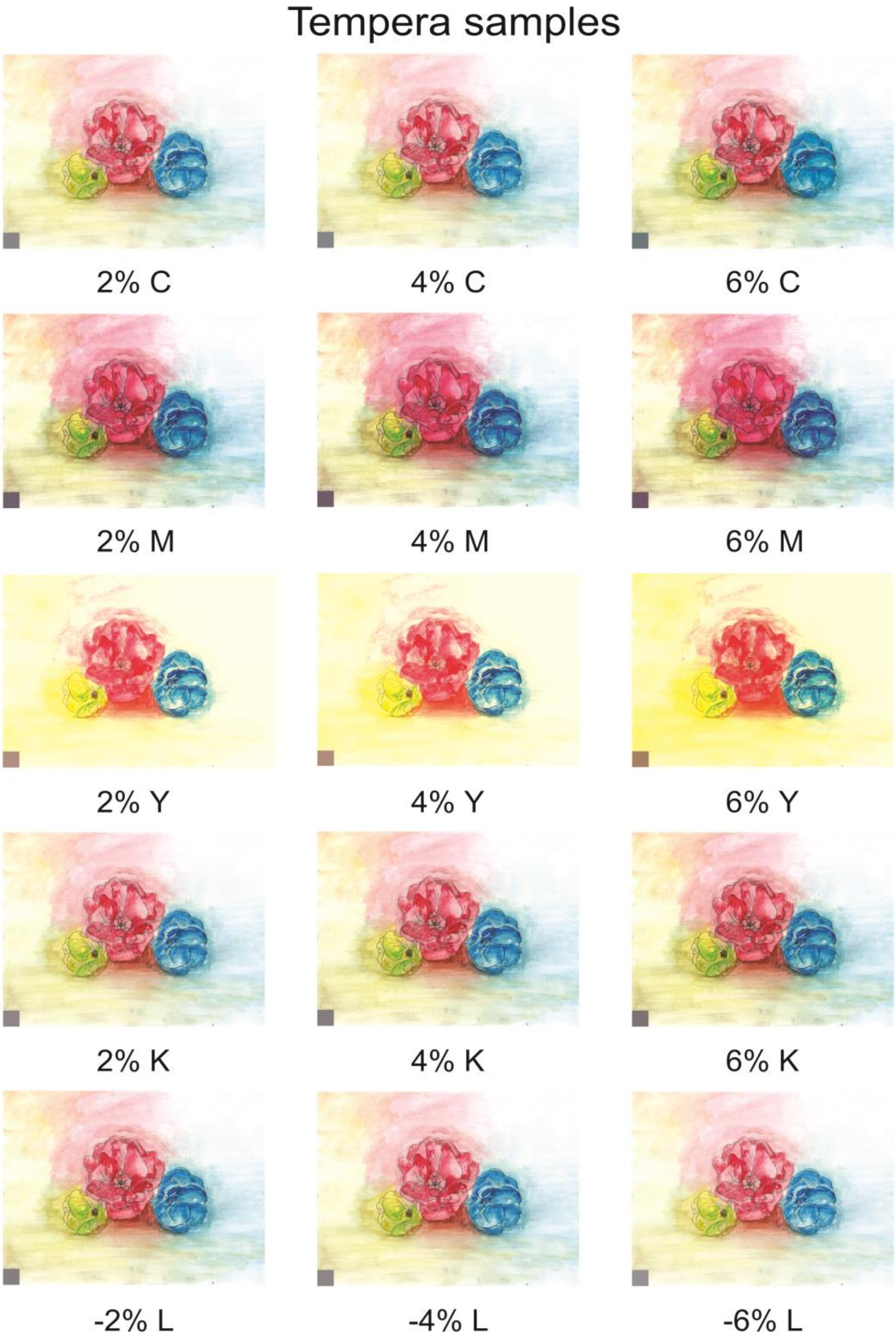


Figure 40. Tempera colour technique reproduction samples with increasing and decreasing values

Subjective changes in the reproduction of images of 15 samples using the Oil colour technique with increasing and decreasing values, finding the similarity and comparison with the original painting under different light sources through visual perception (Figure 41).

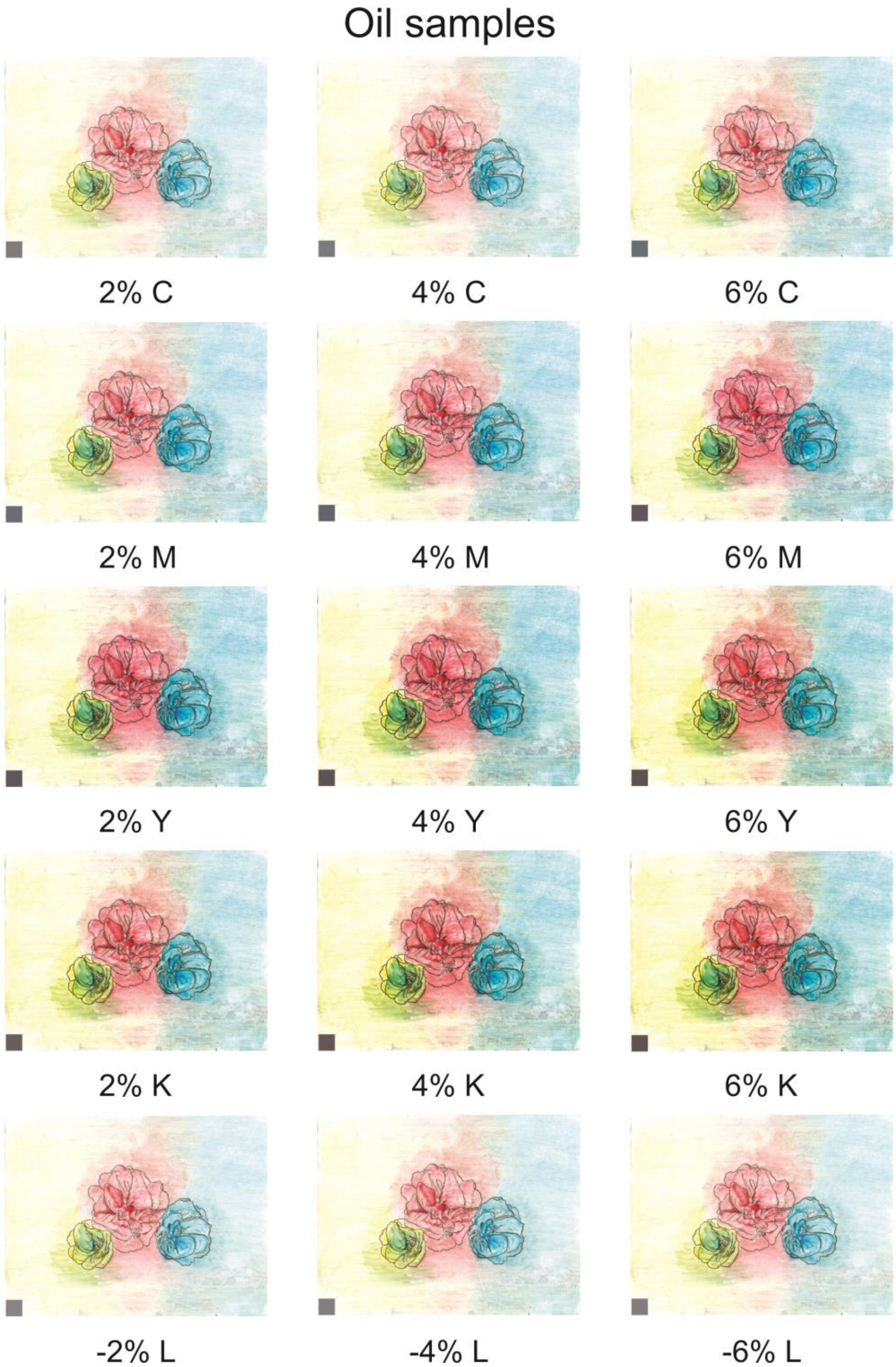


Figure 41. Oil-colour technique reproduction samples with increasing and decreasing values

Subjective variations of the image reproduction of 15 samples in the acrylic colour method with increased and decreasing values, comparing them to the original artwork through visual perception and determining their similarity (Figure 42).

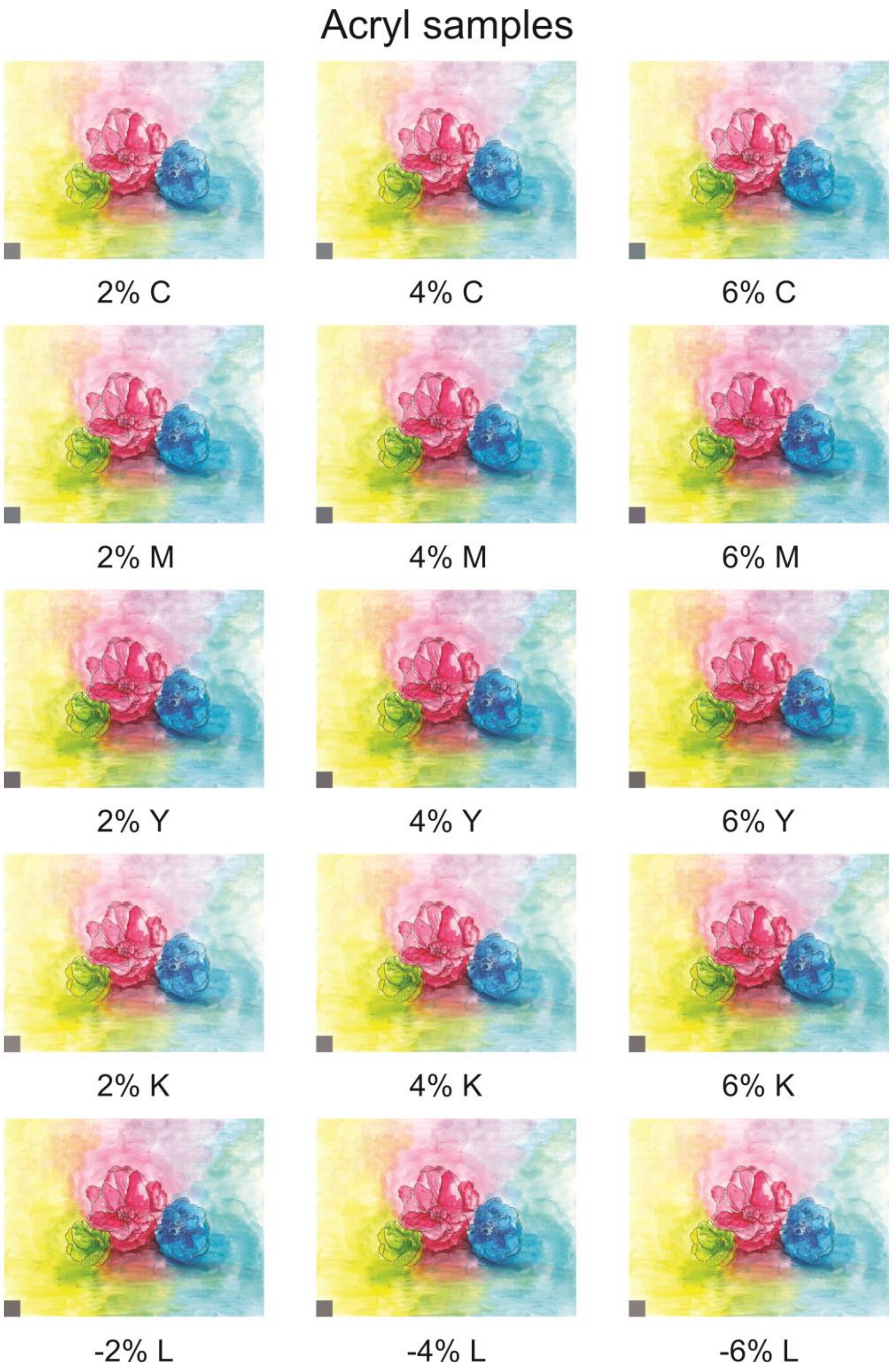


Figure 42. Acrylic colour technique reproduction samples with increasing and decreasing values

The subjective adjustments of 15 pastel colour reproductions of conditions and drying values, comparing them to the original paintings under various lighting conditions, and evaluating how similar they are (Figure 43).

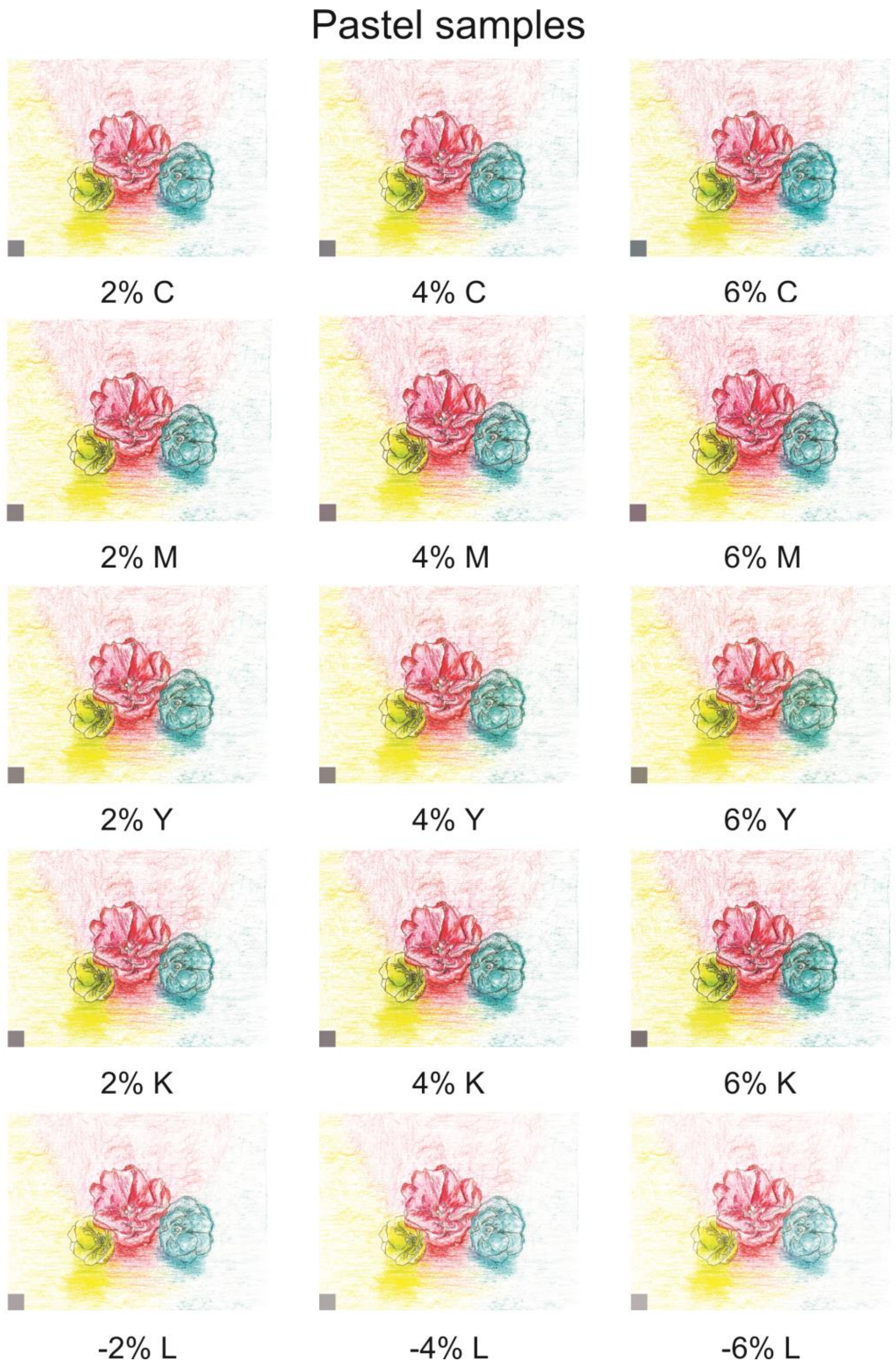


Figure 43. Pastel-colour technique reproduction samples with increasing and decreasing values

Subjective alterations of the reproduction of 15 samples in the water colour technique with increasing and decreasing values, comparing them to the original painting under various lighting sources, and determining their similarities and differences (Figure 44).

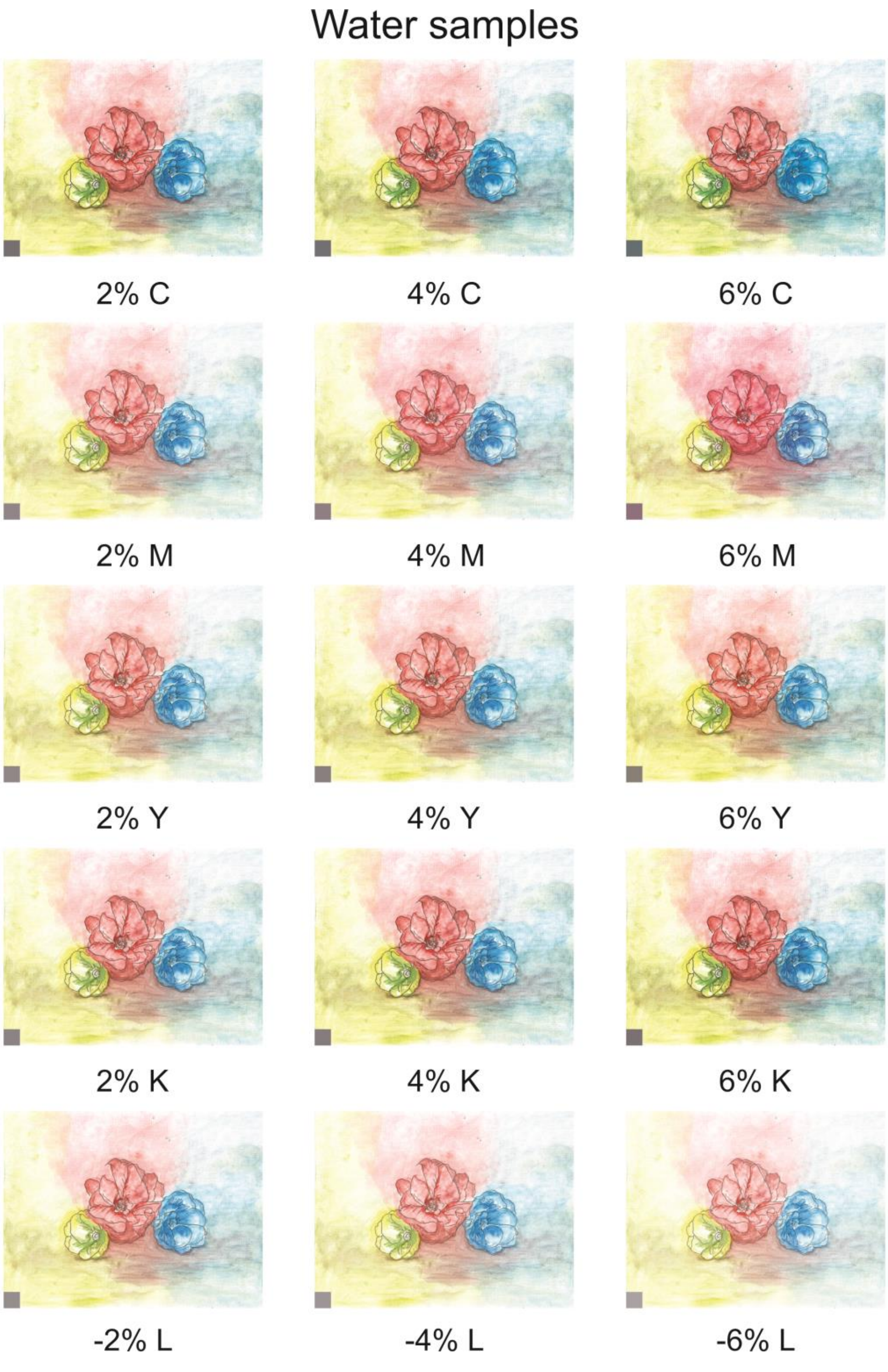


Figure 44. Water colour technique reproduction samples with increasing and decreasing values

The elaborate samples in the digital process have passed through the printing process, reviewing the calibration of the monitor first and then the press.
Reproduction of the images of the paintings was printed on the Xerox colour c70 printer under standardised conditions (Figure 45). The print performances were chosen with a high quality of 100%; this is because the printing process was repeated several times for reasons of searching for the best possible print quality and the suitability of the colours and certain values of L*a*b*.

Figure 45. Device for printing the samples Xerox colour c70 printed press [205]

The characteristics of the printer play a big role in a print, reproduction of a certain material or image, one of the main aspects is the technical specification as well as the continuous calibration of the machine (Table 3).

Table 3. Technical specifications of the Xerox colour c70 printing press

Model C70PRO
Print speed   Colour: up to 70 ppm
Black: up to 75 ppm
Digital Front Ends • Xerox® Integrated Colour Server
Xerox® EX-i C60/C70 Print Server Powered by Fiery®
Xerox® FreeFlow® Print Server Integrated for the Xerox® Colour C60/C70 Printer
Xerox® EX C60/C70 Print Server Powered by Fiery®
Performance

Print speed	Colour: up to 60 / 70 ppm
Black: up to 65 / 75 ppm	
Resolution	Print/Copy: 2400 x 2400 dpi
Scan: 200 x 200, 300 x 300, 400 x 400, 600 x 600 dpi	
Recommended average monthly volume 10,000 - 50,000 pages per month	
Duty cycle	300,000 pages per month
Scan speed Up to 200 ipm colour / 200 ipm black-and-white (2-sided, 8.5 x 11" / A4)	
Line Screens 600, 300, 200 and 150 Clustered Dot, 200 Rotated Line Screen	

The paper for the printing of the samples was used Xerox Colotech + with a thickness of 300g mat within the A3 format (Figure 46), were extended 5 images type of reproduction of the paintings that simultaneously had the same paper with the original paintings.

Figure 46. Paper type Xerox Colotech + material used for paintings and sample reproduction [205]

Technical specifications of the paper material used in the original paintings and the reproduced samples (Table 4).

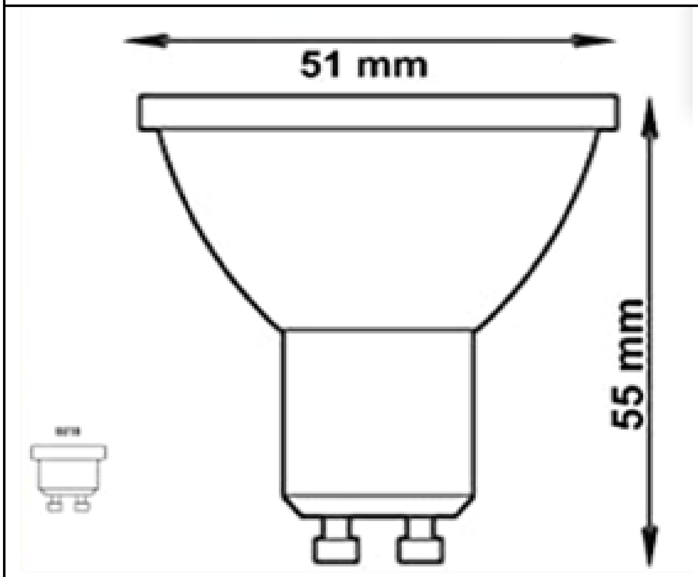
Table 4. Technical specifications of paper type Xerox Colotech+

Specifications	**XEROX COLOTECH +**
UNSPSC Code	14111507
Weight	23.4kg
Brand	Xerox
Categories	Paper & Card
Category	Card
Colour	White
Dimensions	420x297mm
Eco-Aware	Yes
Environment Support	FSC Certified
Grammage	300gsm
Manufacturer	Xerox
Size	A3
Type	Card

In this research to compare and achieving the similarities of each original paintings with reproduction images through visual perception, five different light sources, all of which are Osram reflector Light brand, instead of Wolfram Light - Illuminant A.

The technical specifications of Osram LED light 3000K (warm white) have special features from other lighting such as CCT, lm, Ra (Table 5).

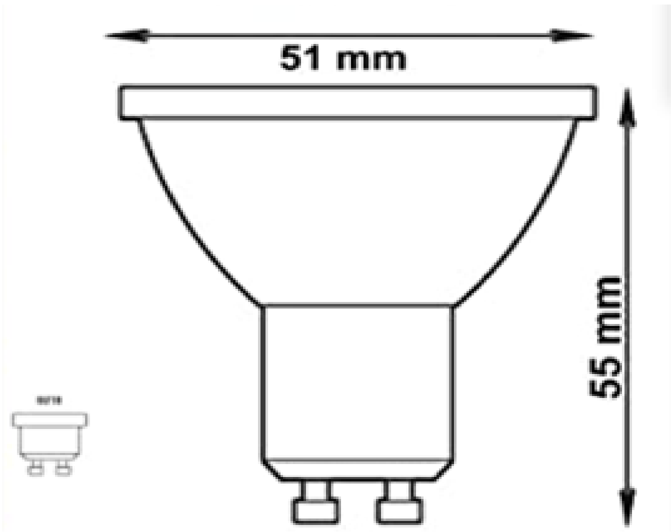
Table 5. Technical specifications of Osram LED Light 3000K

OSRAM LED LIGHT 3000K PRODUCT DATASHEET
P MR16 35 36° 4.3 W/3000K GU5.3 Nominal wattage 4.3w/ 50W
Nominal voltage 220-240 Light colour (designation) Warm White
Colour temperature 3000 K Luminous flux 350 lm
Colour rendering index Ra ≥90 Beam angle 36 °


The technical specifications of the Osram LED light 4000K (neutral white) have special features from other lighting such as CCT, lm, and Ra (Table 6).

Table 6. Technical specifications of Osram LED Light 4000K

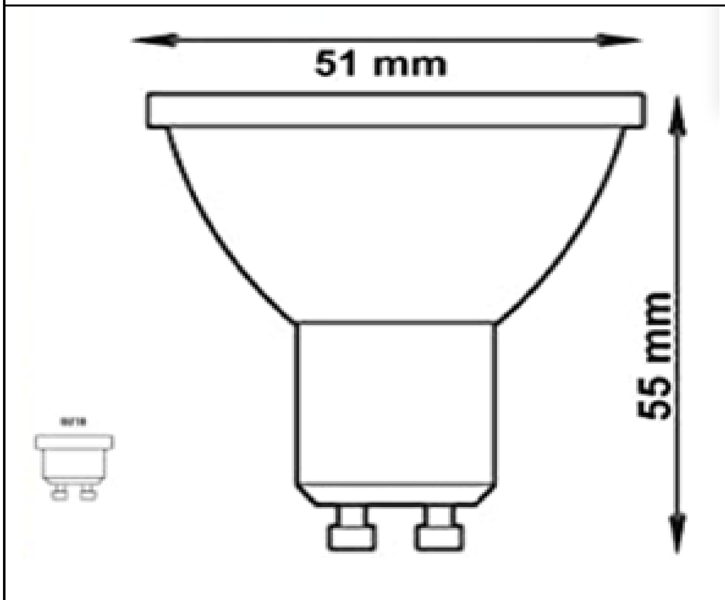
OSRAM LED LIGHT 4000K
PRODUCT DATASHEET
PAR16 50 36- GU10
Nominal wattage 4.3 w/ 50W
Nominal voltage 220-240 Light colour (designation) Neutral White
Colour temperature 4000K
Luminous flux 350 lm Colour rendering index Ra >90 Beam angle 36 °



The technical specifications of the Osram LED 6500K light (cool white) have special features from other lighting such as CCT, lm, Ra (Table 7).

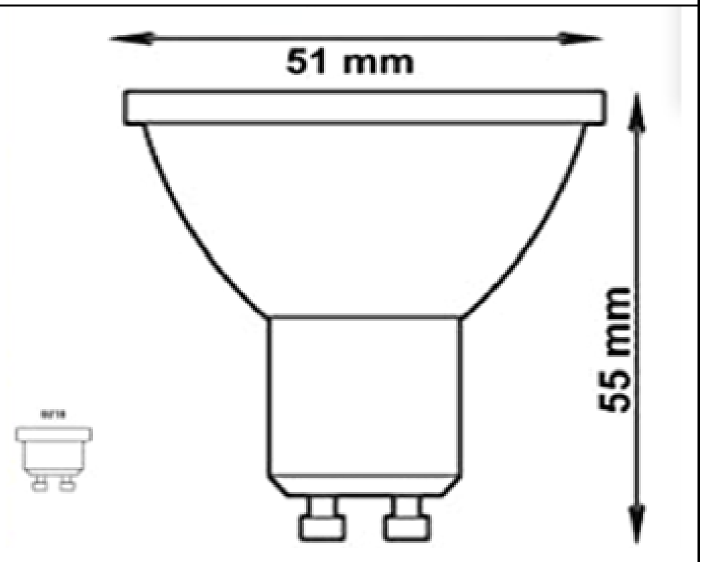
Table 7. Technical specifications of Osram 6500K LED Light

OSRAM LED LIGHT 6500K
PRODUCT DATASHEET PAR16 50 36- GU10 Nominal wattage 2.6 w/ 35W
Nominal voltage 220-240
Light colour (designation) Cool Daylight
Colour temperature 6500K
Luminous flux 230 lm Colour rendering index Ra>90
Beam angle 36 °



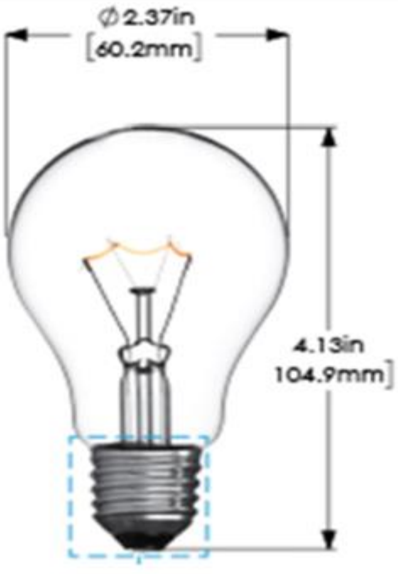
The technical specifications of the Osram Halogen light 3000K (warm white) have special features and the highest colour rendering index Ra >100, CCT from other lighting (Table 8).

Table 8. Technical specifications of Osram Halogen Light 3000K

OSRAM HALOGEN LIGHT
PRODUCT DATASHEET DECOSTAR 51s 44860WFL
Nominal wattage 20 W
Nominal voltage 12 V
Light colour (designation) Warm White
Colour temperature 3000 K
Luminous flux 200 lm Colour rendering index Ra>100
Beam angle 36 °


The technical specifications of Wolfram Light- Illuminant A 2800K (warm white) have the highest CRI, Ra >100 from other lighting, CCT, lm, as it shown in (Table 9).

Table 9. Technical specifications of Wolfram Light- Illuminant A

WOLFRAM LIGHT- ILLUMINANT A PRODUCT DATASHEET
WOLFRAM 34816 Nominal wattage 5 W
Nominal voltage 24 V Light colour (designation) Warm White
Colour temperature 2800 K
Luminous flux 415-460 lm
Colour rendering index Ra>100 Beam angle 36 °


Software for measuring and analysing colour is available from BabelColor under the names CT&A and PatchTool. Printers, pre-press teams, photographers, colour management experts, lighting professionals, as well as expert amateurs and enthusiasts, all utilise the software. Both Windows and Mac can use CT&A and PatchTool. With this software, the CRI of the light sources is measured by using the new methods, technical memorandum (TM 30) developed by Illuminating Engineering Society (IES) (Figure 47). The instrument used in the software BabelColor CT&A software to measure the nm of light sources was i1Pro / i1Pro 2 (XRGA). The i1Pro device is a colour spectrophotometer that can measure many aspects of light, such as its brightness or intensity. The luminous flux, also known as the amount of light falling on a surface, may be precisely measured by i1Pro, and is expressed in lumens (lm).

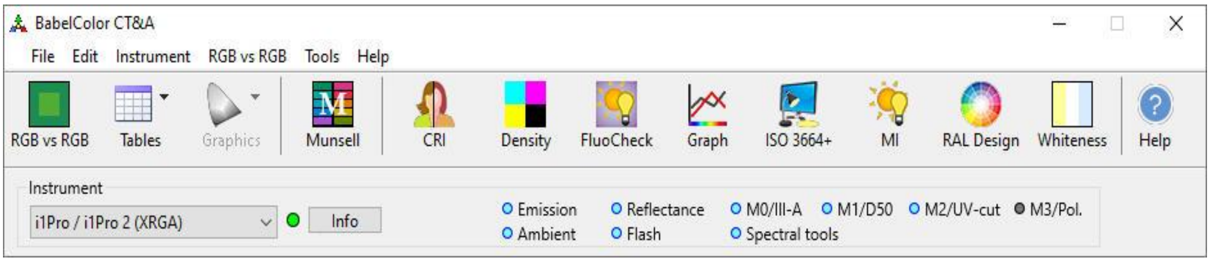


Figure 47. CT&A and PatchTool. With this software, the CRI [206]

The i1 Pro 3 x-rite pantone (holographic diffraction grating with 128-pixel diode array) with integrated wavelength analysis, it measures the spectral distribution, chromaticity, and colour temperature of light, among other aspects of light. These data can be helpful for several purposes, including display calibration, colour management in the printing sector, and characterization of light sources (Figure 48).

Figure 48. Device of light measuring i1 Pro 3 x-rite pantone [207]

7.1.4 Subjective research and survey analysis

he visual analysis of the experimental segment was conducted utilizing a broad spectrum of participants. This diverse group comprised individuals identified as laypersons, lacking professional expertise or experience within the field. Their task encompassed the assessment of photographic imagery through concurrent evaluation and comparison with the original visual stimuli. It is imperative to note that the surveyor cohort possessed no direct familiarity with the intricacies of metamerism, yet their collective interest revolved around aspects of visual observation, communication, perceptual cognition, coloration, and memory congruence.
The comprehensive surveyor ensemble was composed of 45 individuals, with a gender distribution of 23 women and 22 men, spanning an age range from 18 to 60 years. This age distribution further categorized into three distinct groups: 18-25 years (comprising 8 women and 7 men, totalling 15 participants), 25-45 years (comprising 10 women and 10 men, totalling 20 participants), and 45-65 years (comprising 5 women and 5 men, totalling 10 participants).

To ensure the credibility of the participants' visual acuity and simultaneous binocular capabilities, a standard selection process was implemented. Prior to their inclusion in the experiment, all observers underwent a comprehensive binocular examination test, supplemented by the Ishihara test to identify, and assess visual impairments. Only those participants who successfully navigated through these stringent assessments, affirming their possession of normal vision, were included in the experiment. This meticulous selection process guaranteed the adherence to standardized visual conditions within the domain of graphic technology. The experimental procedures transpired within a designated laboratory atelier, encompassing an area of 16 square meters (4 x 4m²). The laboratory atelier interior featured light grey walls, while the windows remained completely sealed, precluding any external light sources. This environment was meticulously designed to maintain consistent and controlled conditions suitable for the exploration of graphic phenomena. Within the laboratory atelier, the point of observation was established with specific parameters: a direct horizontal viewing angle, an angle of incidence set at 60 degrees, illumination originating from a 30-degree angle, sample observation from a 40-degree angle, and positioning at an average adult eye level, specifically at a height of 1500mm, maintaining an elevation of 4000mm above the laboratory floor. This strategic arrangement was precisely configured to adhere to standardized conditions within the field of graphic technology, ensuring the reproducibility and validity of the experimental outcomes. Figure 49, illustrates the spatial arrangement, emphasizing the placement and orientation of the visual stimuli. The dimensions of the artworks under examination adhered to the format of 250x320 mm, enhancing the precision and consistency of the visual analysis.

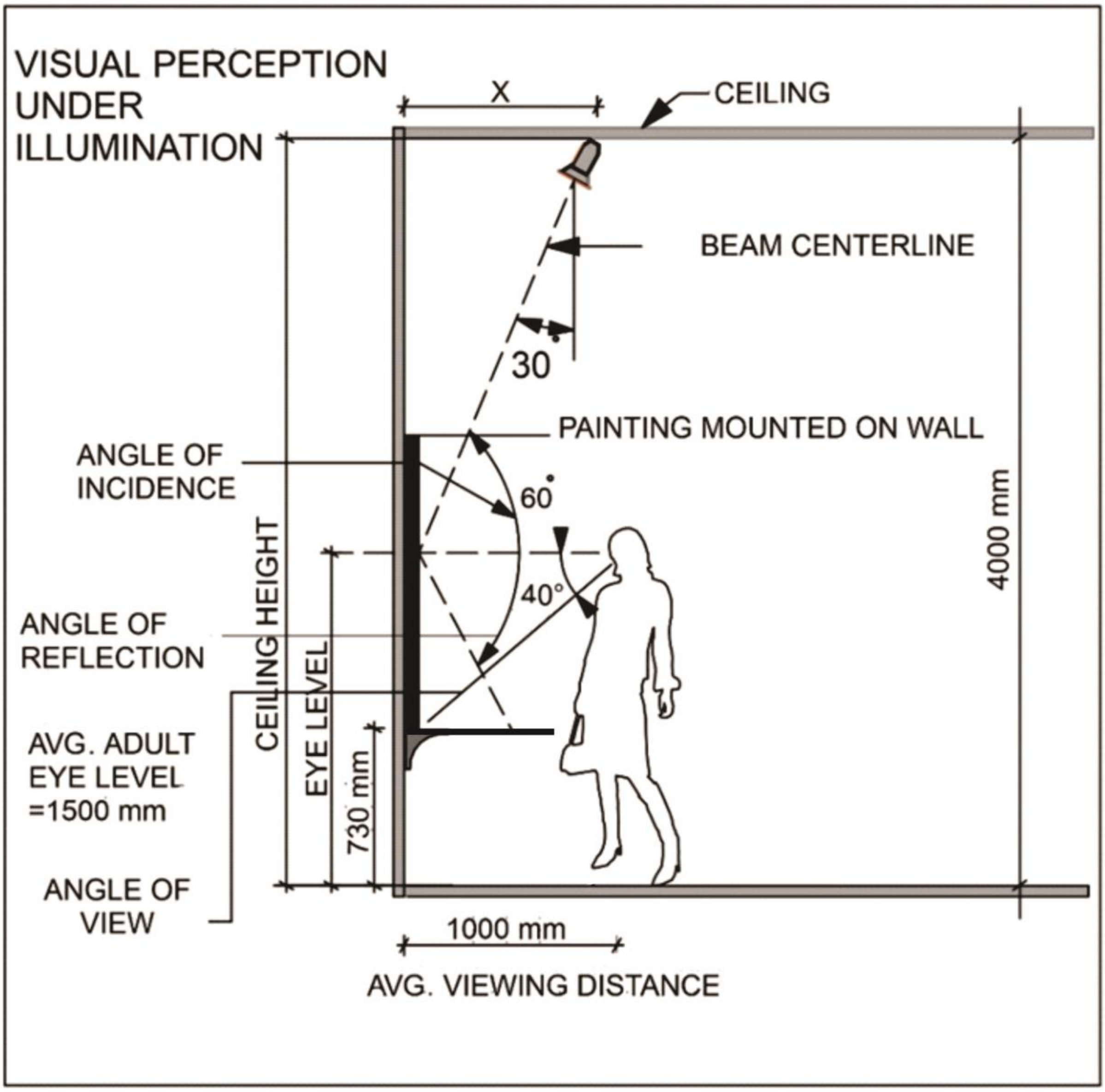


Figure 49. Visual research experiment

The subject's distance from the works placed was 1000mm, the works on the wall were placed 1500mm high, and the observers were standing on feet, while the samples are placed on the table in the visual corner of 30 ° at a height of 730mm (above the floor), to ensure that all participants, regardless of body height, had an average of the same height and had a straight point of view with the paintings. Average of the level of the adult eye = 1500 mm above the floor. Reflexion of the light angle of 30 ° with the distance from the wall 1000mm.

8. RESULTS AND DISCUSSIONS

8.1 Subjective results and discussions

The visual outcomes encompass an integral component of the investigation, focusing on tempera colour paintings subjected to diverse lighting conditions, including LED Light at 3000K, LED Light at 4000K, LED Light at 6500K, Wolfram Light (I.A), and Halogen Light. Within the context of this research, the primary objective revolves around the assessment of meticulously chosen samples that exhibit the highest degree of similarity to the original reference. To this end, a comprehensive analysis is conducted, elucidating the characteristics of all half-tone images employed in the study. The frequency distribution of these images is meticulously documented, both in terms of individual selections under the illumination of LED light at 3000K, and subsequently, in accordance with their hierarchical ranking, as depicted in (Figure 50). This systematic approach affords a detailed insight into the selection process and enables a nuanced understanding of the visual outcomes achieved under distinct lighting conditions.

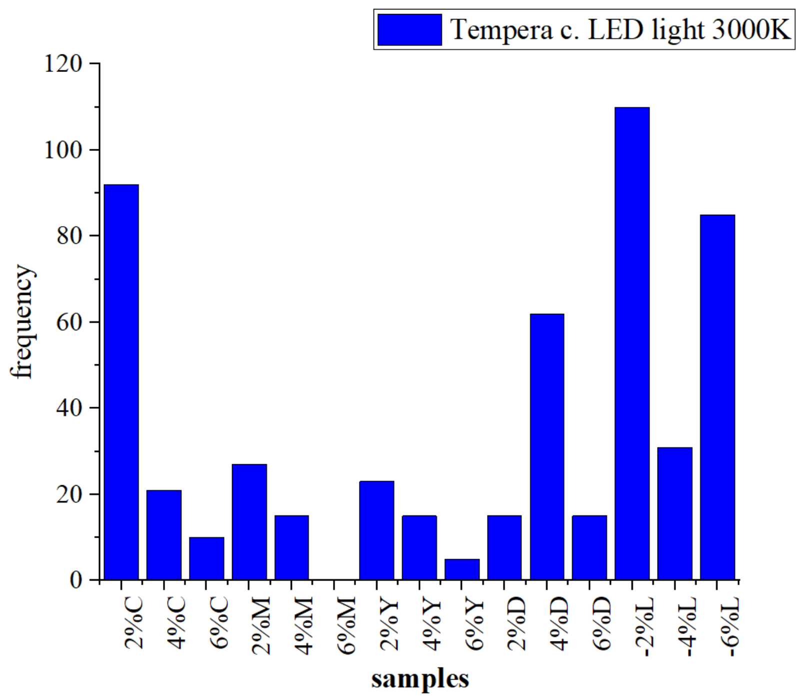


Figure 50. Description of subjective evaluation of different samples under the LED light 3000K

Also, changing colour or pigments creates a different observation of light by the other techniques, an indication of the right human perception.

The samples chosen more similar to the original in the 3000K tempera technique under LED light, the classified frequencies are summarised with the most 5 chosen with the most frequency, for comparison to be performed (Figure 51).

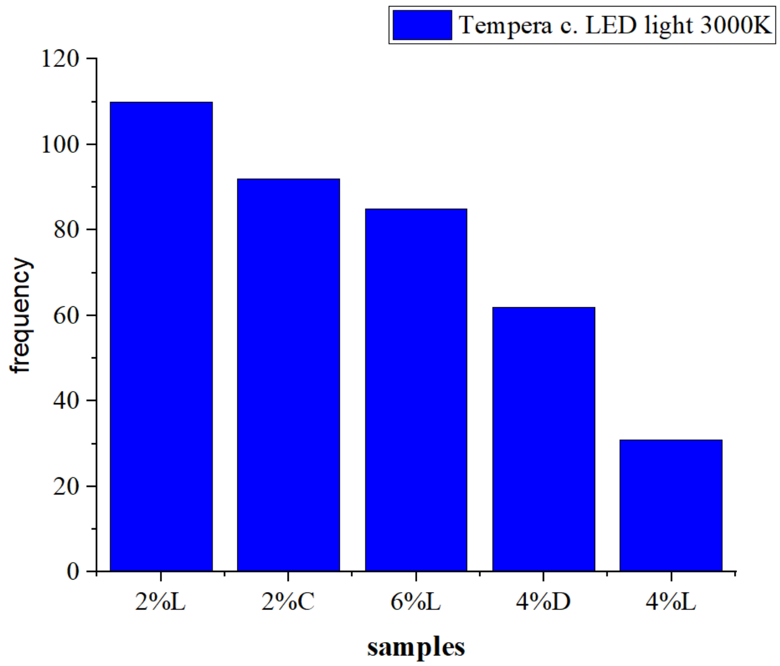


Figure 51. Best match samples of tempera colour under LED light 3000K

Through visual perception of observers, and individual selection, the frequencies of the most likely to original of tempera colour testing (Figure 50) under LED light 3000K. These are ranked by dividing the points from the best one by 5 points to 1 as the last selection. According to the results of analysis, there is a diversity of selection or nuances that observers have evaluated as nuances with a small difference of half tone. The first nuance, -2%L, and the second, 2%C, are the most similar to the smallest percentage of the tonality change. However, summarising the points at (Figure 51), we see 3 samples of different percentages (%) of the same nuance of colour. We can say that the nuances -2L, -4L, and -6L, are most acceptable from the observers under the LED light 3000K in the visual aspect. Based on the visual methods under the LED light 4000K of tempera colour painting, observers in an individual way have evaluated the most similar nuances to the original, which means that we have different results according to the individual or changing the lighting.

The presentation of subjective evaluation of samples compared to the original painting of tempera colour under the LED light 4000K is presented all nuances, comparing between half-tones of colours (Figure 52).

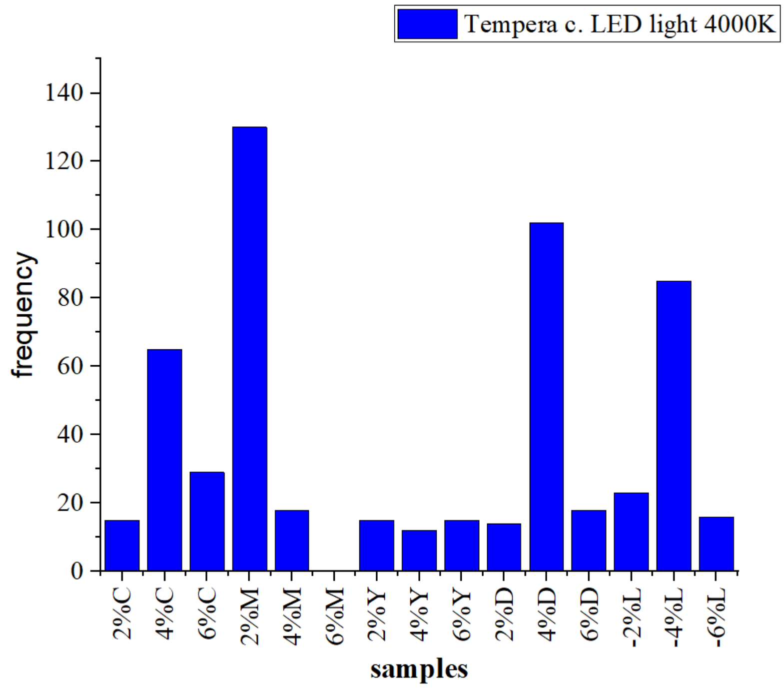


Figure 52. Description of subjective evaluation of different samples under the LED light 4000K

The best samples selected under the different lighting conditions were made to see closely the subjective evaluation. Despite the same conditions of the same research methodology, the evaluation and results are seen to be different. Under the LED light 4000K, the most 5 similar samples to the original are selected (Figure 53).

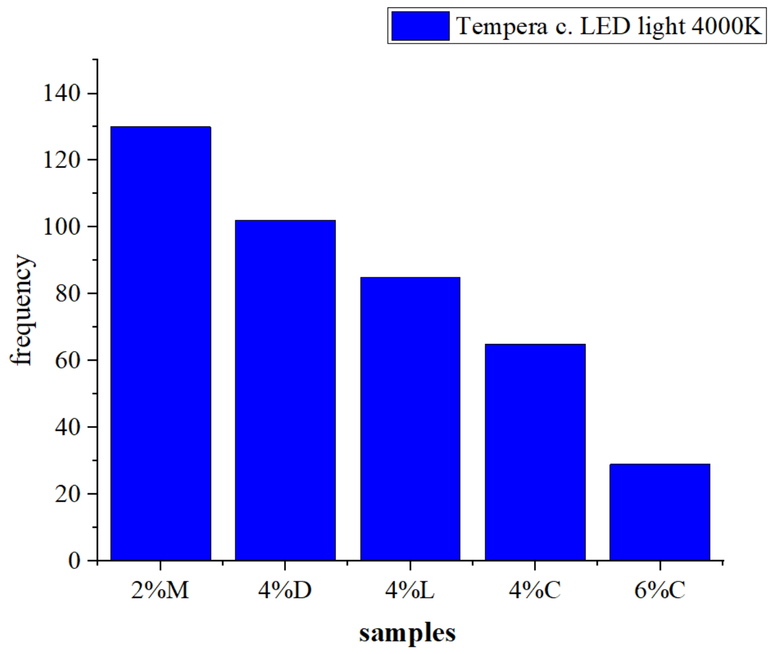


Figure 53. Best match samples of tempera colour under LED Light 4000K

In presentation of tempera colour results (Figure 53) under LED light 4000K, it can be seen that the best selection is 2M, while the most general evaluation by observers averages 4% of different nuances and the last 6%. Therefore, the percentage increase in nuances of the selected samples is seen.

According to the same method of subjective evaluation in selection of the most similar samples matched to the original painting in tempera colours under the LED light 6500K, all samples have been evaluated by the possibility of finding the closest similarity (Figure 54).

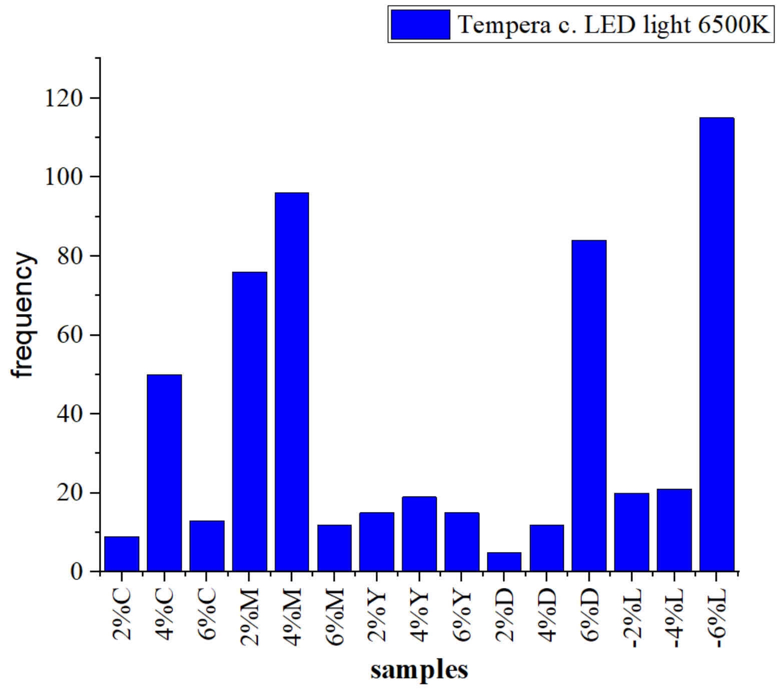


Figure 54. Description of subjective evaluation of different samples in tempera colour under the LED light 6500K

Although by this presentation 5 most similar to the original have been selected, by the classified evaluation or the most points (Figure 55).

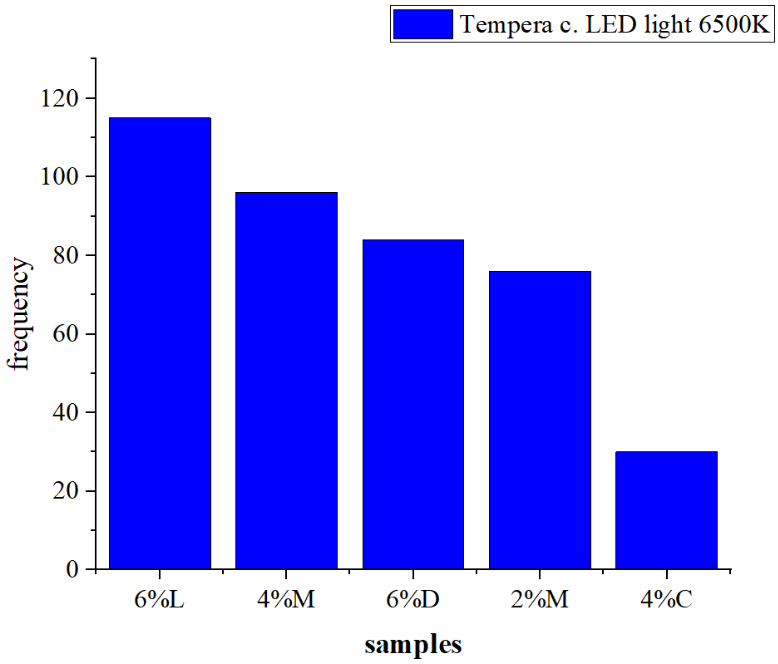


Figure 55. Best match samples of Tempera colour under LED Light 6500K

The results shown in (Figure 54) under the LED light 6500K, the sample -6%L is clearly higher and different from other samples. This is because of the light colour LED light 6500K makes the observer to see the most similar the nuance with the difference -6% as a result of the reflexion in more white to blue, this indicates in subjective perception of the observer. Whereas other nuances 4%M, 6%D, 2%M, 4%C are positive nuances with different percentages, where is seen a distinction form the first sample, because of the darker percentage.

Under the lighting of Wolfram light (Illuminant A), the presented samples were evaluated according to the light reflexion and its SPD. Here, we summarise the general evaluation together with the technique with tempera colours (Figure 56).

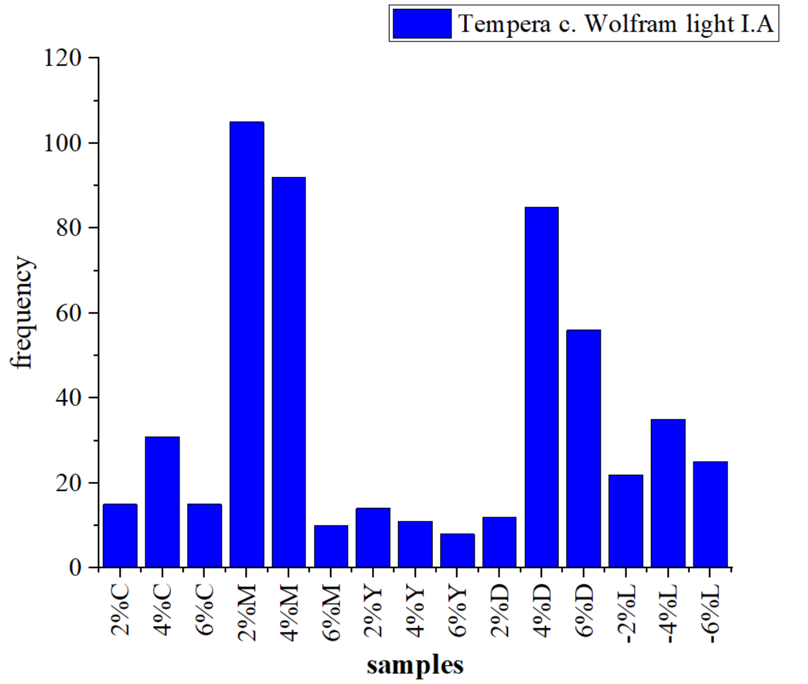


Figure 56. Description of subjective evaluation of different samples in tempera colour under Wolfram Light I. A

Although by this presentation 5 most similar to the original have been selected, by the classified evaluation or the most subjective selected ones (Figure 57).

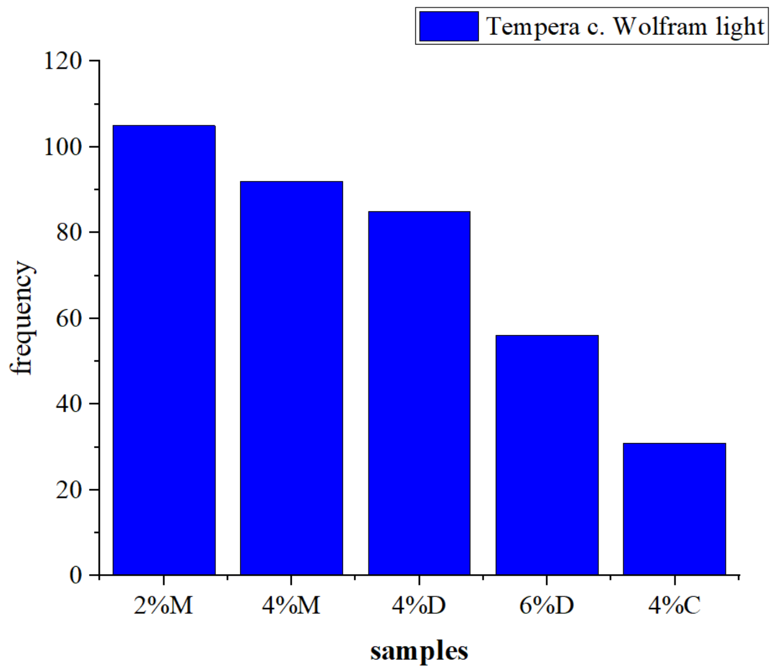


Figure 57. Best match samples of tempera colour under Wolfram Light

The results shown under light Wolfram light (Illuminant A) as shown in (Figure 56), percentage tones of warm shades such as 2%M, 4%M are subjectively chosen more, without excluding the shades 4%D and 6%D which are darker, and the last 4%C. Under this lighting, the most selected shades are clearly the warmer and darker shades. This is due to the SPD of Wolfram Light that its spectrum is warmer, this reacts to the choice of the observers to see the most similar shade because of the reflexion of the red colour of the illumination; this is clearly seen in the subjective perception of the observers.

Under the lighting of halogen light, the presented samples were evaluated according to the light reflexion and its SPD. Here, the general evaluation alongside the technique with tempera colours (Figure 58).

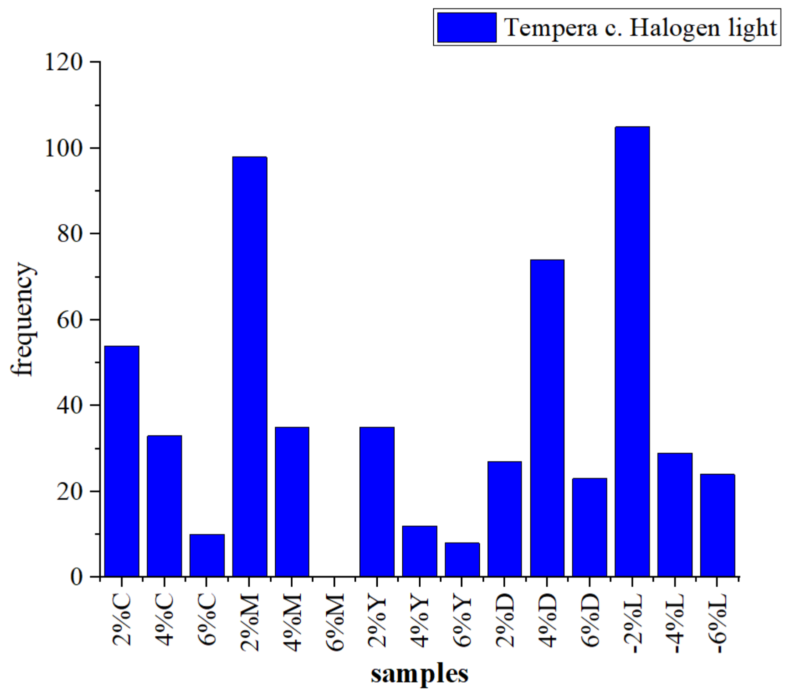


Figure 58. Description of subjective evaluation of different samples under Halogen Light

The description of best matching and comparison through subjective results of different samples under halogen light (Figure 59).

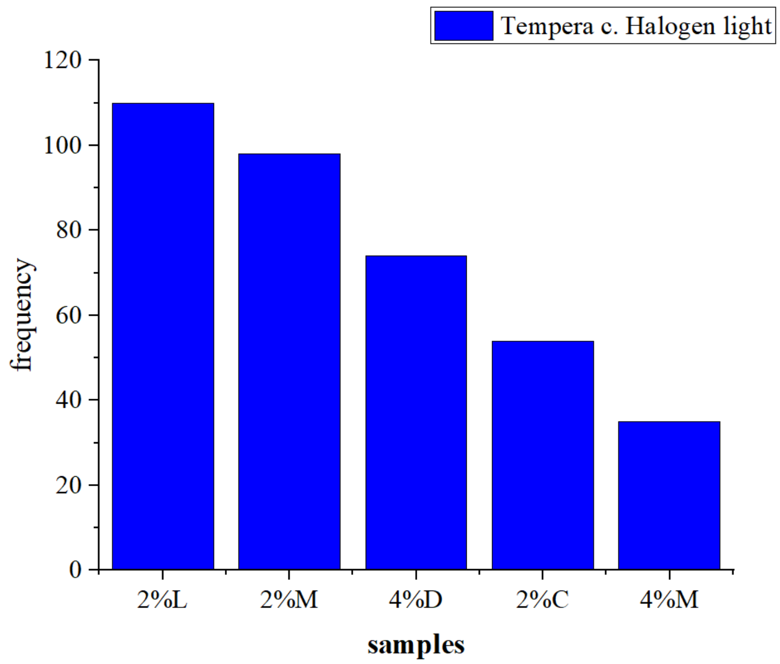


Figure 59. Best match samples of tempera colour under Halogen Light

The results achieved under Halogen Light (Figure 59), are mostly mixed. However, the results are of the smallest percentage as the closest choice 2%M, then the second 2%C while as the third choice we again have a magenta shade 4%M, as the next result we have 2%Y and the last also with a small percentage 2%D. This is due to the SPD of Halogen Light that its spectrum is warmer and mostly used on museum and galleries, this reacts to the choice of the observers to see the most similar shade because of the reflexion on small percentages of different half-colour tone images. This is clearly seen in the subjective perception of the observers under halogen light.

By summarising the overall results of all samples in the common aspect under all illuminations, some selected sample points are seen, which find suitability under different illuminations. However, in terms of subjective evaluation, we have a choice (Figure 60).

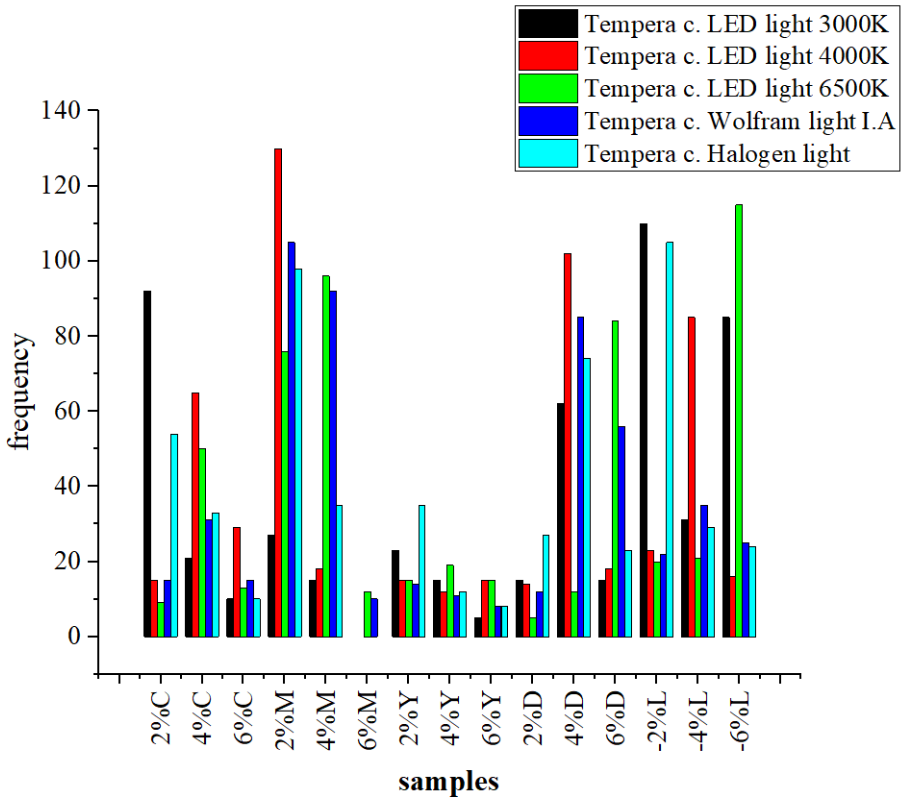


Figure 60. Subjective results of samples under different light sources

Visual results of oil painting and sample under different light sources as: LED Light 3000K, LED Light 4000K, LED Light 6500K, Wolfram light, Halogen Light. Changing the colour or lighting technique creates a different visual perception of light reflexion or observation than other techniques.

All the half tone images used, and their frequency are described according to the individual selection of the observer under the 3000K LED light in the Oil colour technique and in the order as follows (Figure 61).

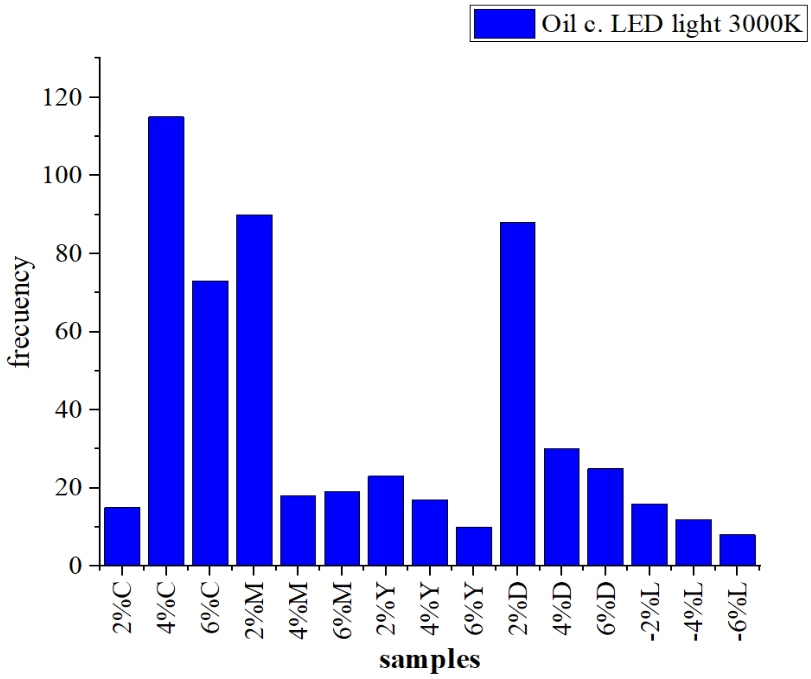


Figure 61. Description of the subjective evaluation of different samples on oil colour under LED Light 3000K

The categorised frequency is summed using the top five samples that are the most similar to the original in the oil-colour method under the 3000K LED light, in order to make a comparison as it shown in (Figure 62).

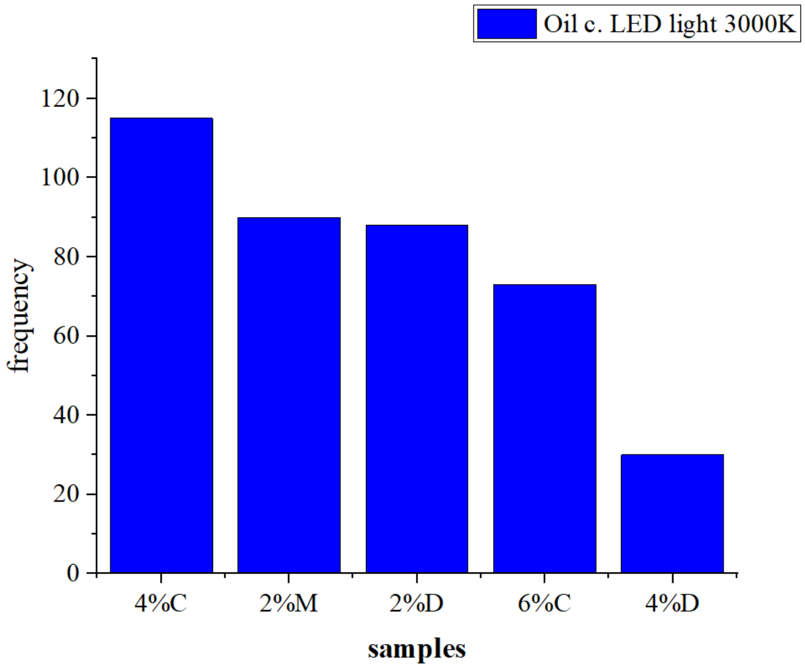


Figure 62. Best match samples of oil colour under LED Light 3000K

According to the results of analysis (Figure 62), we see a diversity of selection or nuances that the observers have evaluated as shades with differences on the half tone. The first nuance 4%C and the fourth 6%C result in the most similar nuances to the tonality change, the second shade 2%M and the third 2%D according to the frequency are the half tones with the smallest percentage, continuing with the last shade with a more darker tone 4%D.
Different lightings and colours have their own specific characteristics, at the same time when we combine or change one or the other.

In the presentation of the subjective samples of oil colour samples next to the original painting under the illumination of LED light 4000K, these results were achieved between half tones of colours. In the (Figure 63) it is shown oil colours observe light differently from acrylic colours.

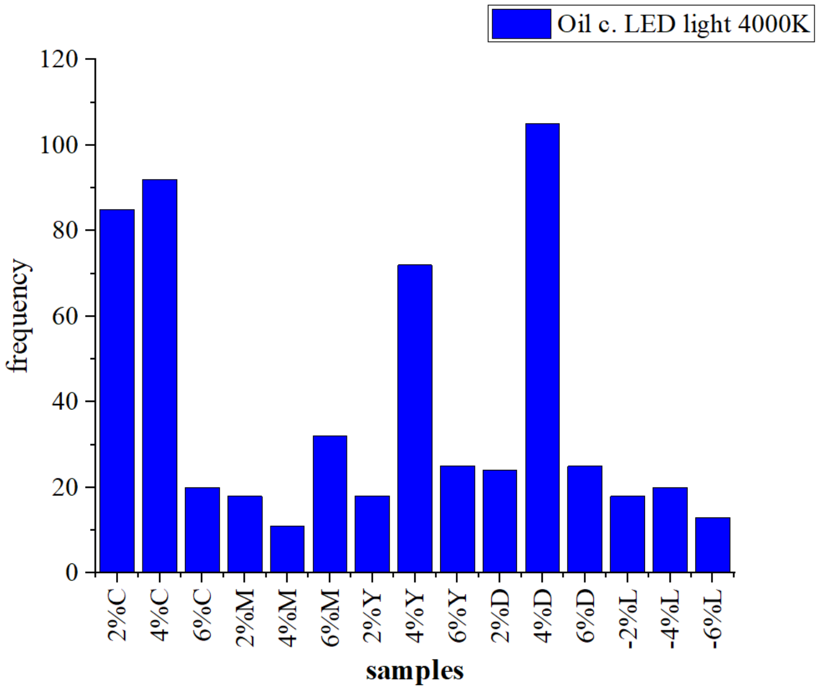


Figure 63. Description of the subjective evaluation of different samples on oil colour under LED Light 4000K

The best five samples in the oil colour technique under the LED light 4000K that most closely resemble the original are used to total the category frequency in order to construct a comparison (Figure 64).

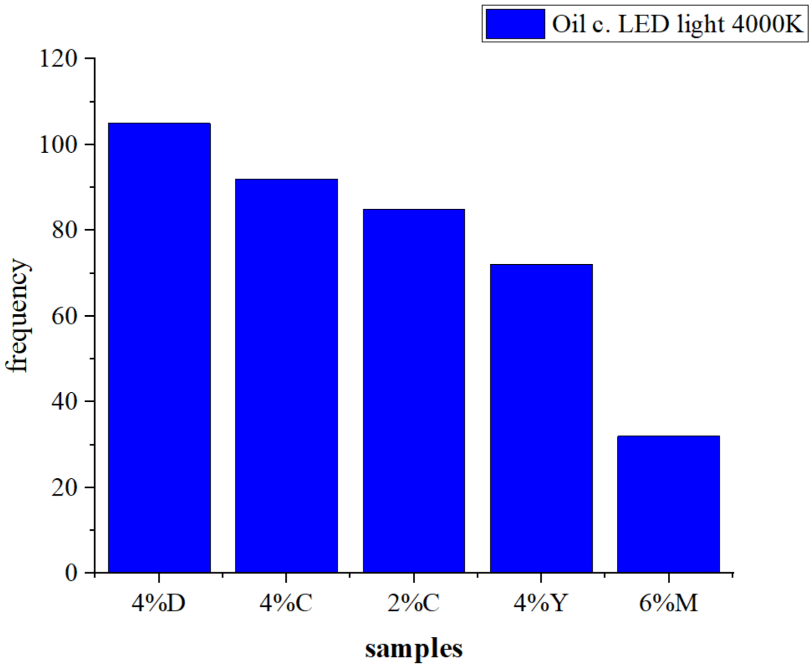


Figure 64. Best match samples of oil colour under LED Light 4000K

According to the selection of the results (Figure 64), closest to the original oil painting under 4000K LED light, we can see that the average evaluation by the observers is 4% of half tone, from the best 4%D, 4%C and 4%Y, with except for the third halftone with the smallest percentage of 2%C and the last one of the highest percentage 6%M.

All samples are analysed with the potential to identify the closest resemblance using the same approach of subjective assessment in the selection of the most similar samples that match the original oil painting under 6500K LED light (Figure 65).

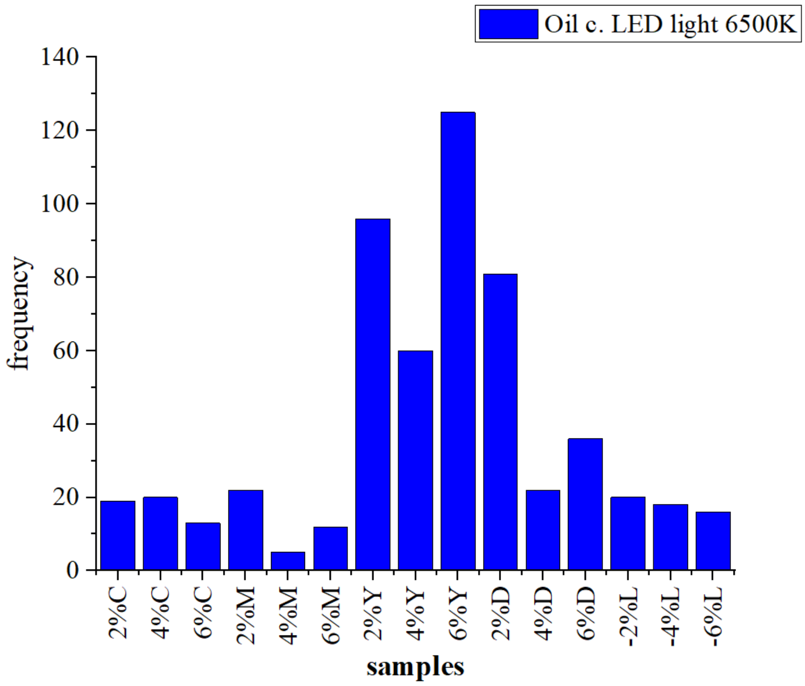


Figure 65. Description of the subjective evaluation of different samples on oil colour under LED Light 6500K

In the presentation of the results of oil painting under the illumination of the LED light 6500K, the 5 closest samples have been selected (Figure 66).

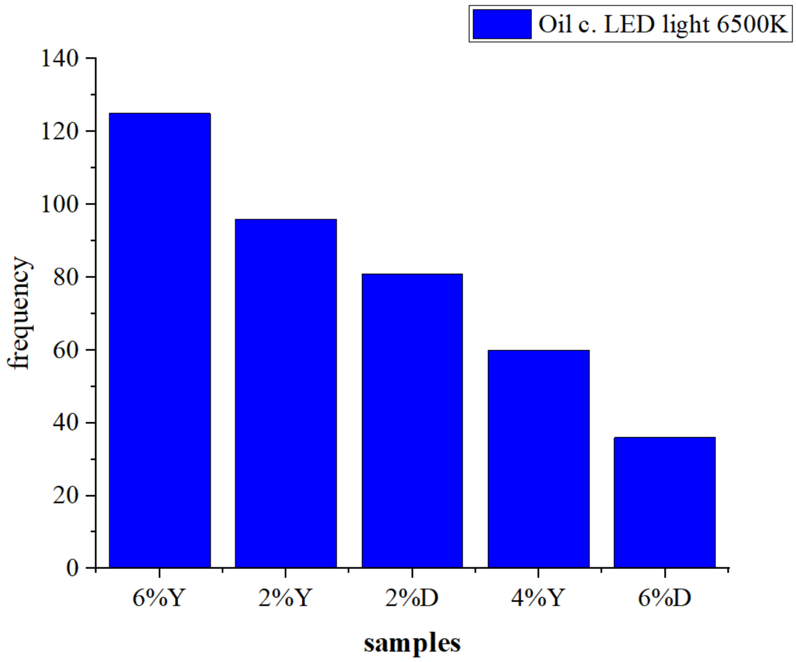


Figure 66. Best match samples of oil colour under LED Light 6500K

The results shown under the LED light 6500K at (Figure 66), starts with the best choice 6%Y is clearly higher, and as seen in these colours the observers are more attracted by the yellow shades and continues with the second shade 2%Y and the fourth 4 %Y, where the three shades of the same colour from the other samples are presented. While the third shade 2%D and the last 6%D are the other choices according to subjective appearance. This is because of the oil colours and their composition that they have and the LED light 6500K reacts differently when observing their lighting and reflexion.

The provided samples were evaluated using Wolfram Light (Illuminant A) illumination in accordance with the lighting reflexion and its SPD. Here is included a summary of the overall analysis with the oil painting method (Figure 67).

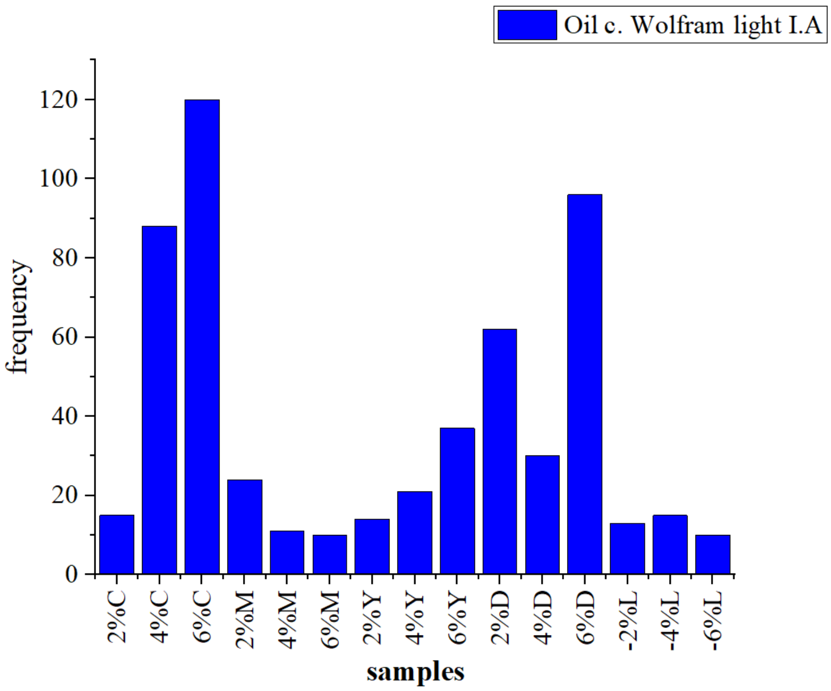


Figure 67. The description of subjective evaluation of different samples under the Wolfram Light I.A

The five that are most comparable to the original have been chosen for this presentation, the categorised evaluation or the most subjective selections have been made (Figure 68).

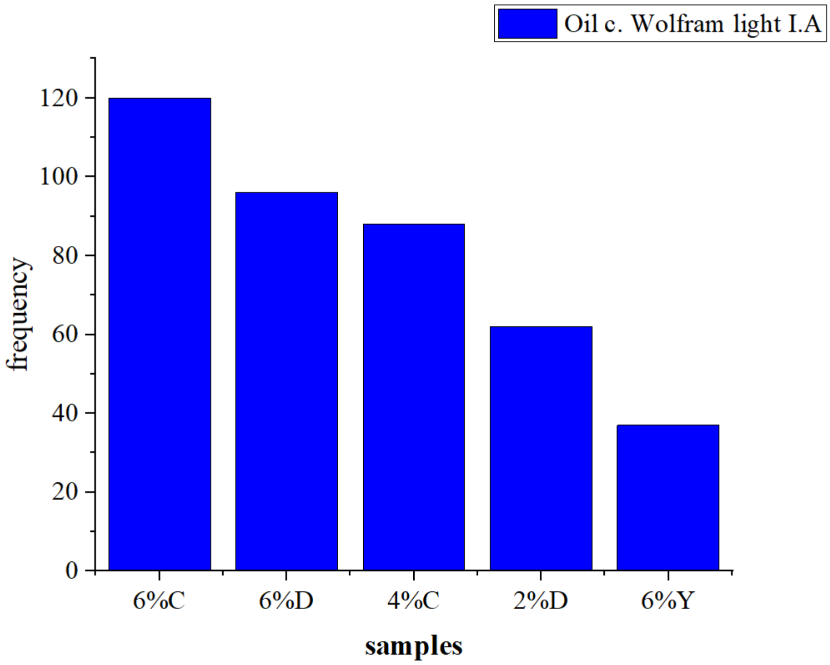


Figure 68. Best match samples of oil colour under Wolfram Light I.A.

Results displayed in (Figure 68) under Wolfram light (Illuminant A), the percentage tones from the shades with the highest percentages such as the first 6%C, the second 6%D and the last 6%Y are subjectively more chosen, not excluding the third shade 4%C and the fourth shade 2%D, which these shades have been chosen twice in different percentages. Under this lighting, the most selected shades are clearly the shades with the highest percentages.

This is due to Wolfram Light's SPD that its spectrum is warmer, also from the Oil-colour technique. This responds to the observer's choice to see the most similar shadow due to the reflection of the lighting colour and the painting technique. These are clearly seen in the subjective aspect of the perception of the observers.

Under the halogen light the presented samples of oil panting techniques, were evaluated according to the lighting reflexion and subjective observers. Here, the general evaluation alongside (Figure 69).

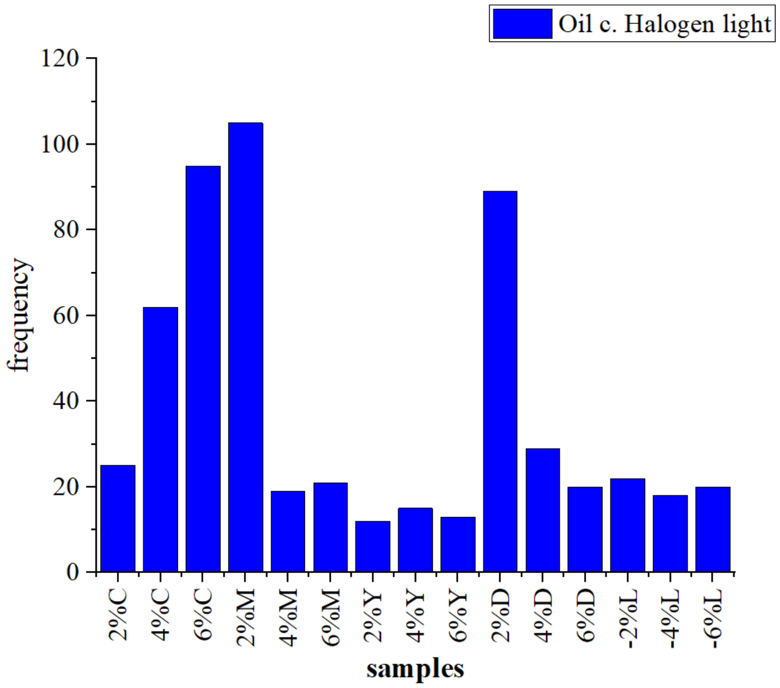


Figure 69. Description of subjective evaluation of different Oil c. samples under Halogen Light

The analysis of the best comparison and matching using the best oil painting samples under halogen light, according to subjective results (Figure 70).

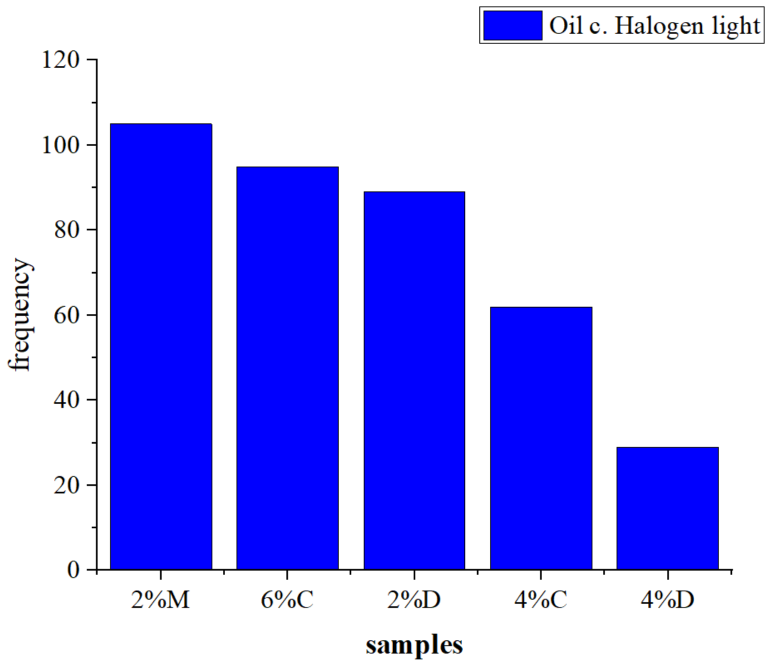


Figure 70. Best match samples of oil colour under Halogen Light

The results achieved under halogen light at (Figure 70) are mostly mixed. However, the best selected result is 2%M while the second sample with a difference in percentage and shade 6%C, followed by the third shade with a small percentage of 2%D, followed by the fourth shade 4% C and the last 4%D. Also, in this lighting, we have two repeated shades with different percentages. It is because of the SPD of halogen light that its spectrum is warmer, and differences between techniques and choices by observers are seen differently.

The offered evaluation of oil painting techniques was assessed based on lighting reflexion and the subjective opinions of the observers under different light sources. The whole evaluation was summarised here as well (Figure 71).

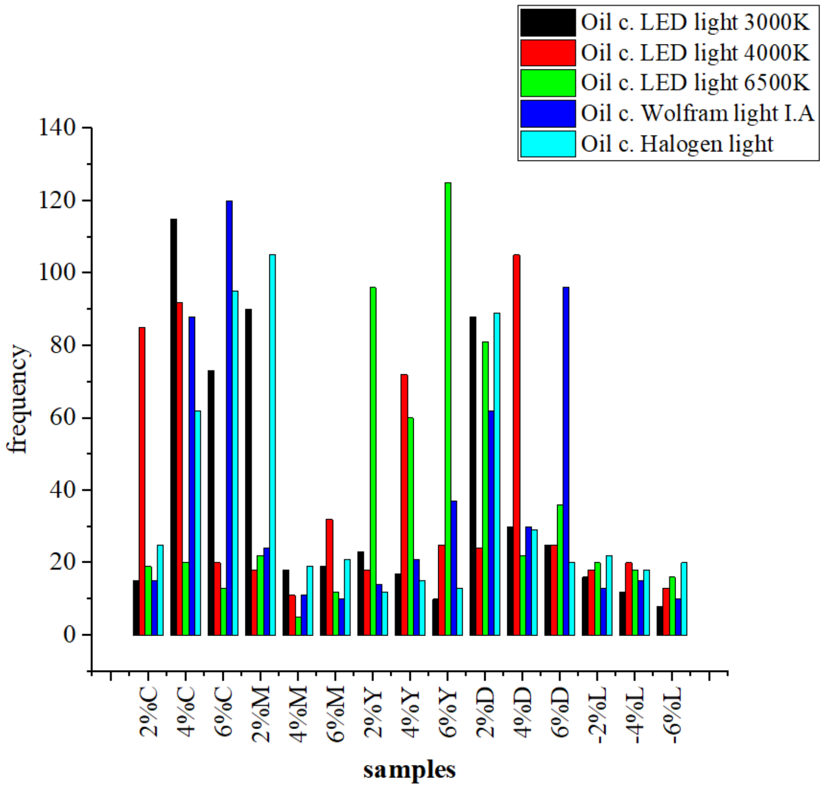


Figure 71. Description of Oil colour samples under different light sources

According to subjective results, the best comparison and matching utilising the best acryl painting samples under LED light 3000K (Figure 72).

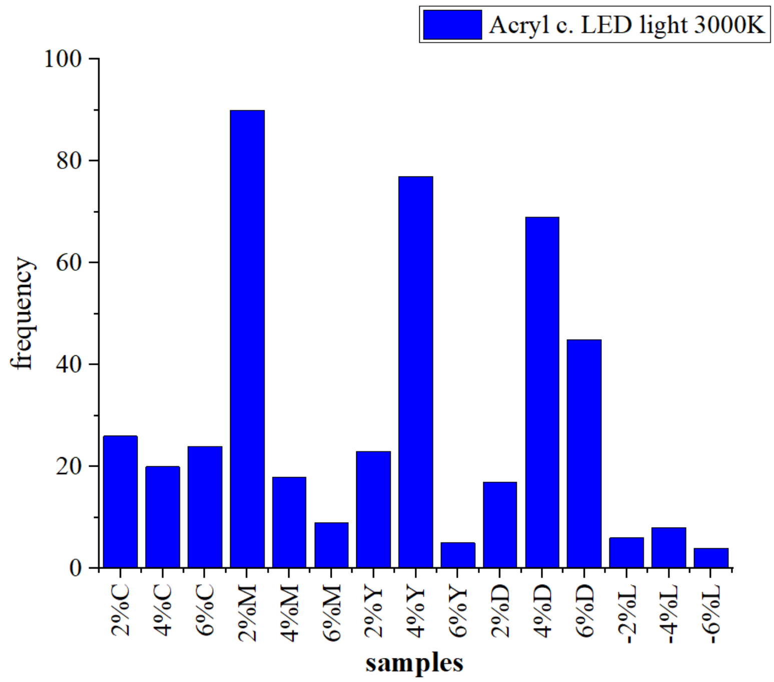


Figure 72. Description of subjective evaluation of different samples of Acryl colour under the LED Light 3000K

Using the best acryl painting samples under light 3000K, the study of the best comparison and matching was performed, with subjective conclusions (Figure 73).

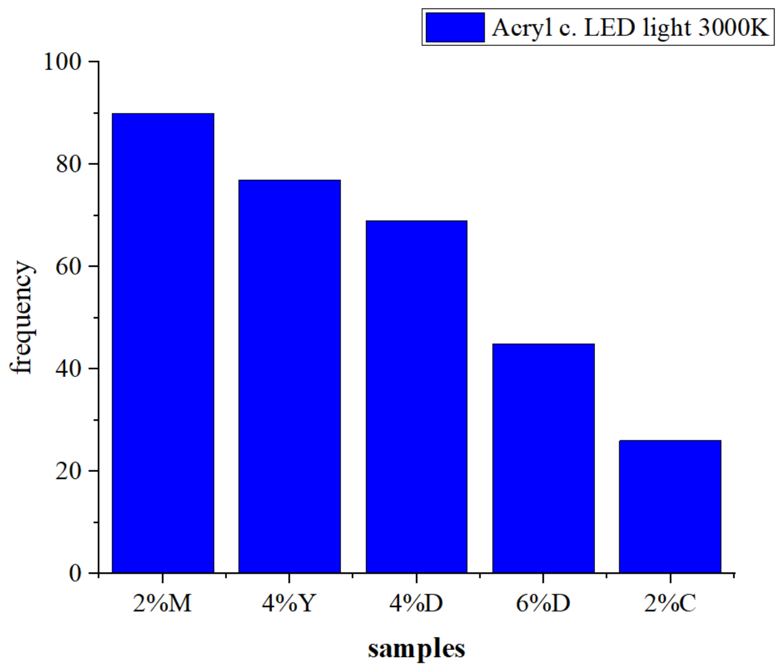


Figure 73. Best match samples of Acryl colour under LED Light 3000K

The analysis's findings at (Figure 73) lead us to detect a variety of selections or subtleties, which observers have classified as shades with variations in the halftone. The most comparable subtleties to the tonality shift are found to be the first nuance 2%M and the last nuance 2%C, followed by the second sample 4%Y and third one 4%D. The hues with the highest percentages, in order of scoring, are followed by the fourth shade with a darker tone, 6%D. When we mix or alter one or the other, varied lighting and colours each have their own unique properties. In this instance, acrylic colours absorb light in different ways.

These findings were obtained between half-tones of colours when the subjective acrylic colour samples were displayed next to the original artwork under the illumination of 4000K LED light (Figure 74).

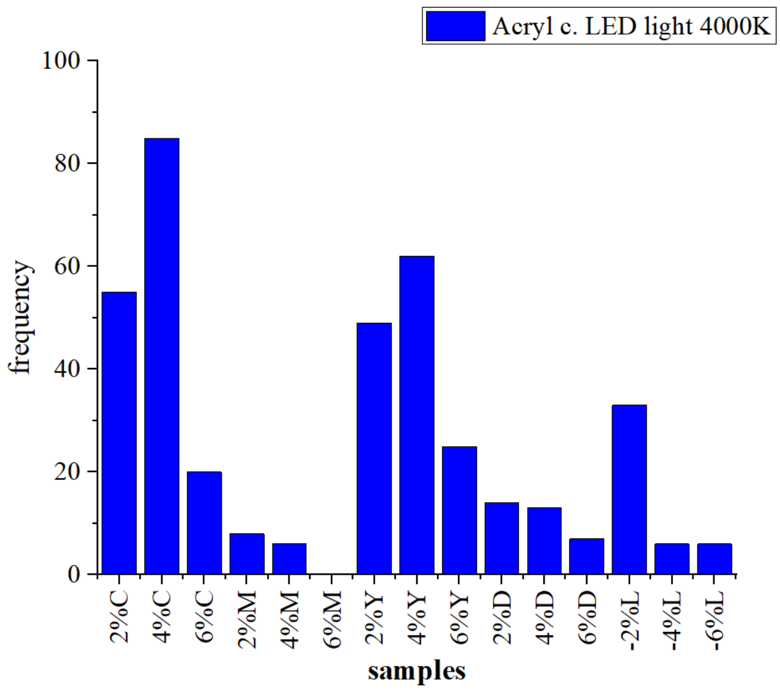


Figure 74. Description of the subjective assessment of different samples of oil colour under LED Light 4000K

The analysis of the best comparison and matching using the best Acryl painting samples under 4000K LED light produced subjectively favourable findings (Figure 75).

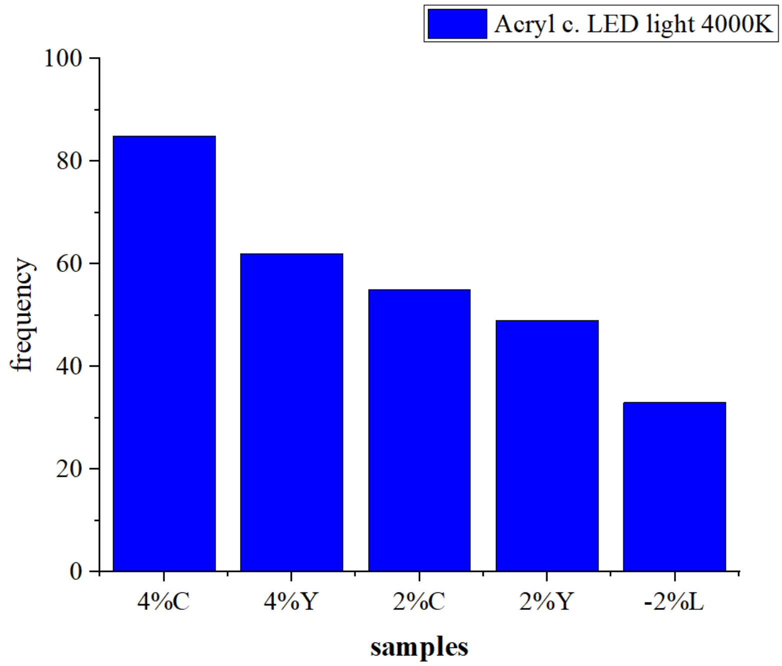


Figure 75. Best match samples of Acryl colour under LED Light 4000K

It is shown that the average evaluation by the observers is in the middle of half tone at (Figure 75), and small of half tone, from the best 4%C, second 4%Y, continuing with the third one 2%C, the fourth sample 2%Y, and the last one -2%L. According to the selection of the results closest to the original acryl painting under LED Light 4000K light. Two variations are reproduced in this experiment, although to varying degrees.

With the same subjective assessment in the selection of the most comparable samples that match the original acrylic painting under LED light 6500K, all samples are evaluated with the ability to discover the closest similarity (Figure 76).

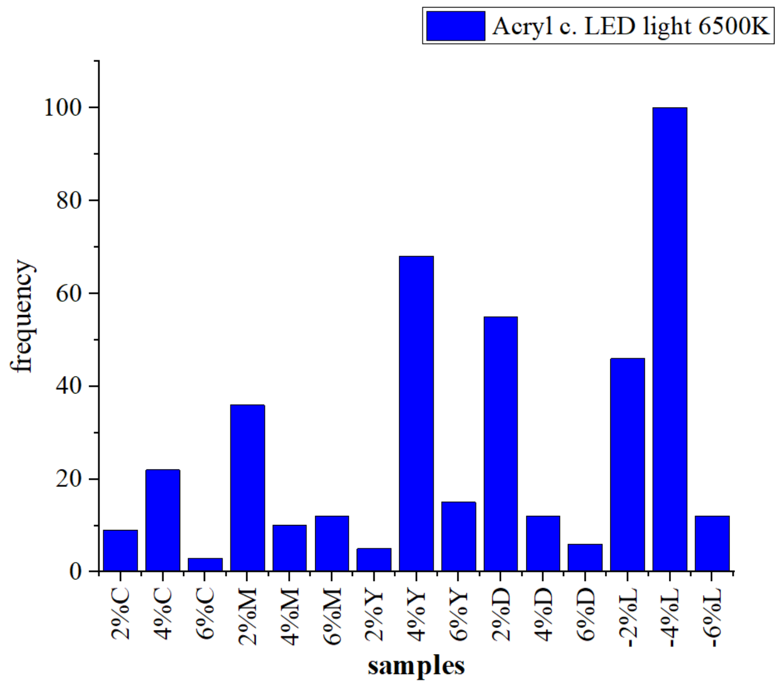


Figure 76. Description of the subjective evaluation of different samples of Acryl colour under LED Light 6500K

Subjectively acceptable results were obtained from the examination of the best comparison and matching utilising the best Acryl painting samples under 6500K LED light (Figure 77).

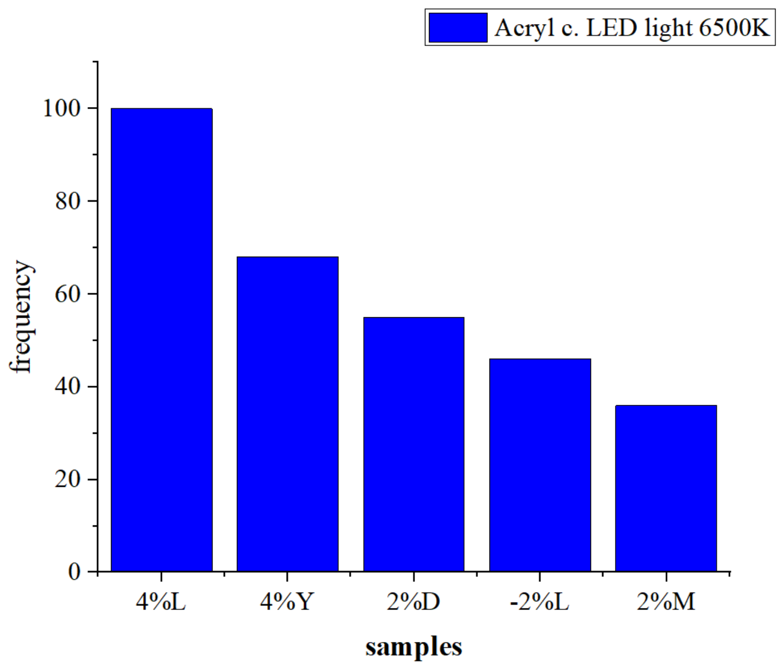


Figure 77. Best match samples of Acryl colour under LED Light 6500K

According to the selection of the results closest to the original Acryl painting under LED Light 6500K, it is demonstrated that the average evaluation by the observers is in the middle and small of half-tonne (Figure 77). It starts with lighter tone from the best 4%L, second 4%Y, by continuing with the third one, 2%D, the fourth sample -2%L, and the last one, 2%M.

In this experiment, different variants are replicated, albeit to different degrees. Using the same subjective evaluation method, all samples were assessed with the ability to identify t that most closely resemble of the original acrylic painting when viewed in Wolfram Light (Figure 78).

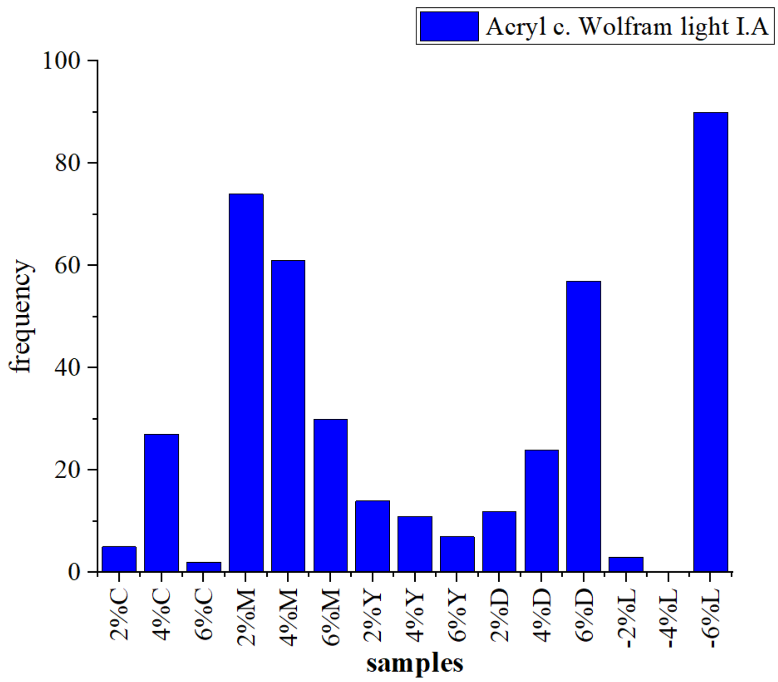


Figure 78. Description of the subjective evaluation of different samples of Acryl colour under Wolfram Light

Subjectively acceptable outcomes were achieved from the assessment of the best comparison and matching using the best Acryl painting samples under Wolfram light (Figure 79).

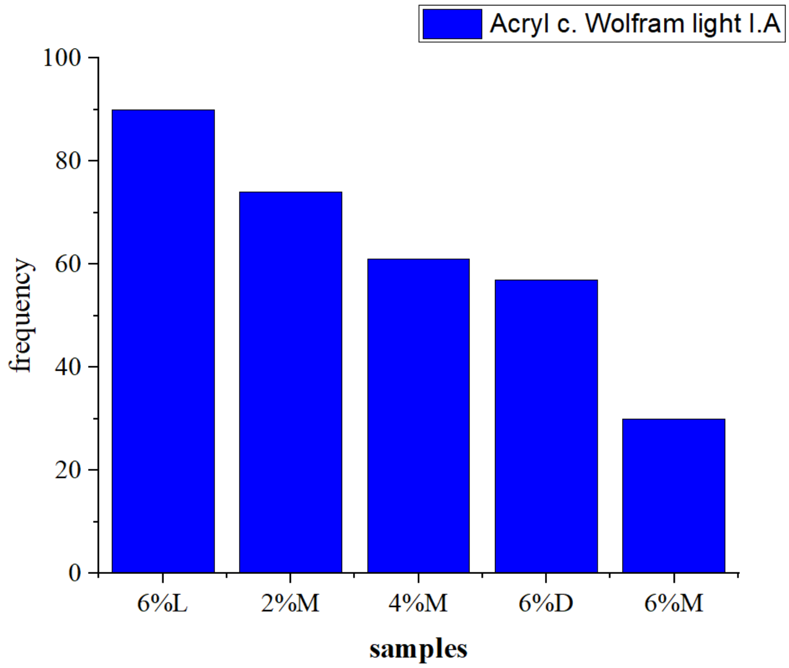


Figure 79. Best match samples of Acryl colour under Wolfram Light

According to the selection of the results closest to the original Acryl painting under Wolfram Light (Figure 79), it is demonstrated that the average evaluation by the observers shows higher percentage of half-tones, and all percentage of magenta nuance are chosen. It starts with lighter tone from the best 6%L, second 2%M, by continuing with the third one 4%M, the fourth sample 6%D, and the last one 6%M.

In this research, different variants and degrees are replicated. All samples are subjectively evaluated using the same technique to determine which ones match the original acrylic artwork when seen in Halogen Light (Figure 80).

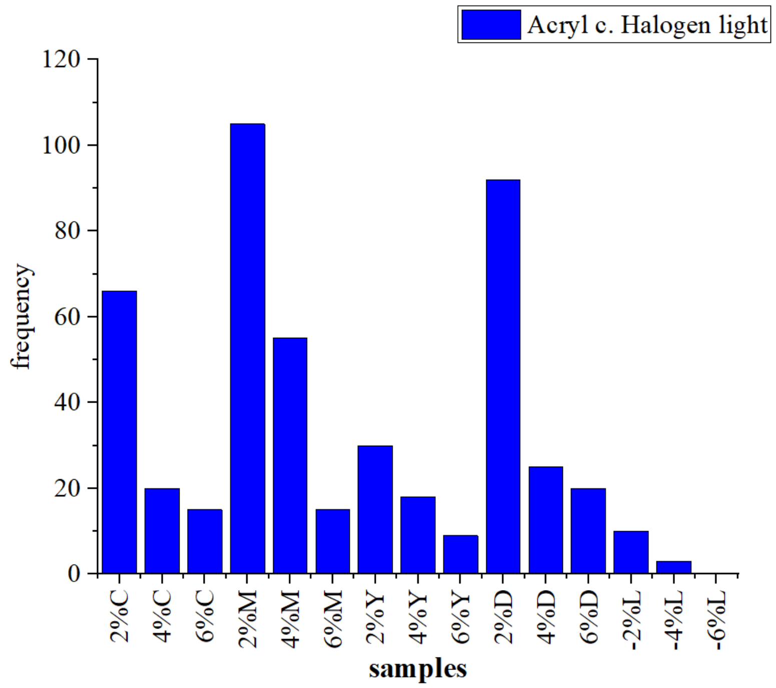


Figure 80. Description of the subjective evaluation of different samples of acryl colour under Halogen light

The evaluation of the best comparison and matching using the best Acryl painting samples under Halogen light produced subjectively satisfactory results (Figure 81).

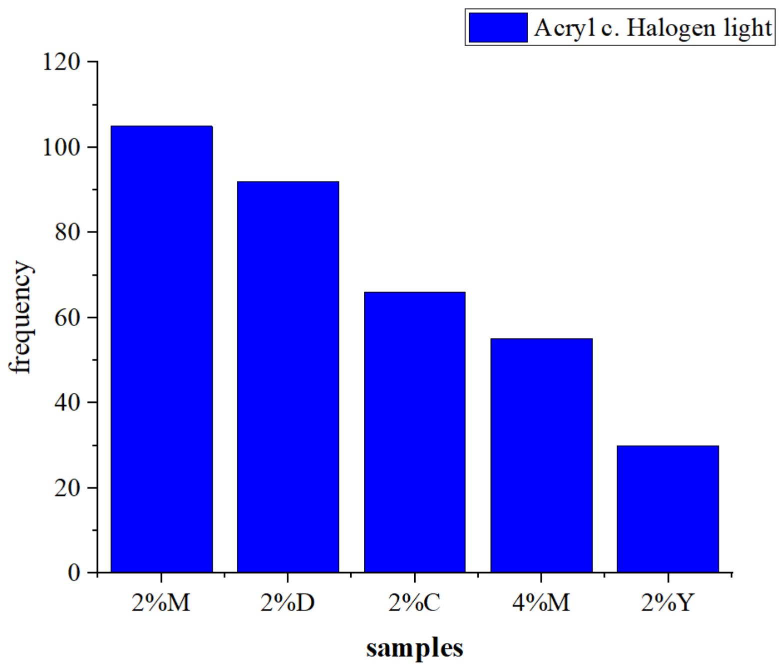


Figure 81. Best match samples of acryl colour under Halogen light

According to the selection of the results closest to the original Acryl painting under Halogen Light (Figure 81), it is demonstrated that the average evaluation by the observer's shows smaller percentage of half tones is mostly chosen.

It starts with magenta tone from the best 2%M, second 2%D, and continues with the third one 2%C, the fourth sample 4%M, and the last one 2%Y.

It is possible to identify certain chosen sample locations that are appropriate under various illuminations by summing the total results of all samples of Acryl colour in the common aspect under all illuminations. However, it has a choice when it comes to subjective evaluation as it shown in (Figure 82).

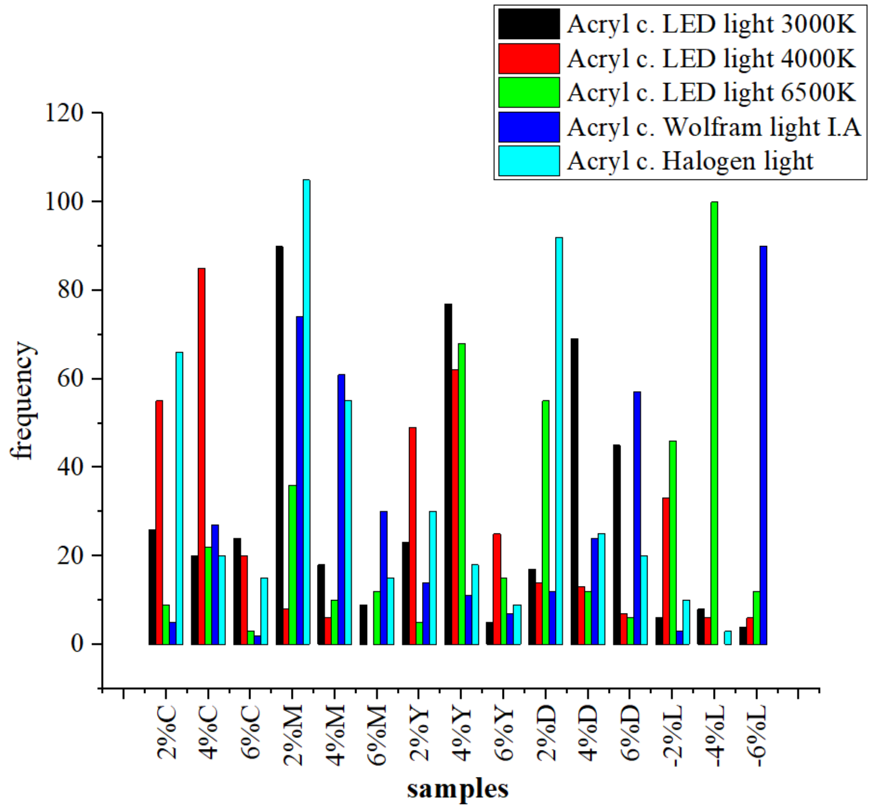


Figure 82. Description of the subjective evaluation of samples of acryl colour under different light sources

Given that the research involves evaluating samples that have been picked based on their similarity to the original sample, all relevant nuances, and their score according to the observer's individual selection on pastel colour under LED light 3000K, and according to the ranking are explained in this manner (Figure 83). Moreover, altering colour or pigments changes the way light is seen using various approaches, providing information on how humans should perceive certain things.

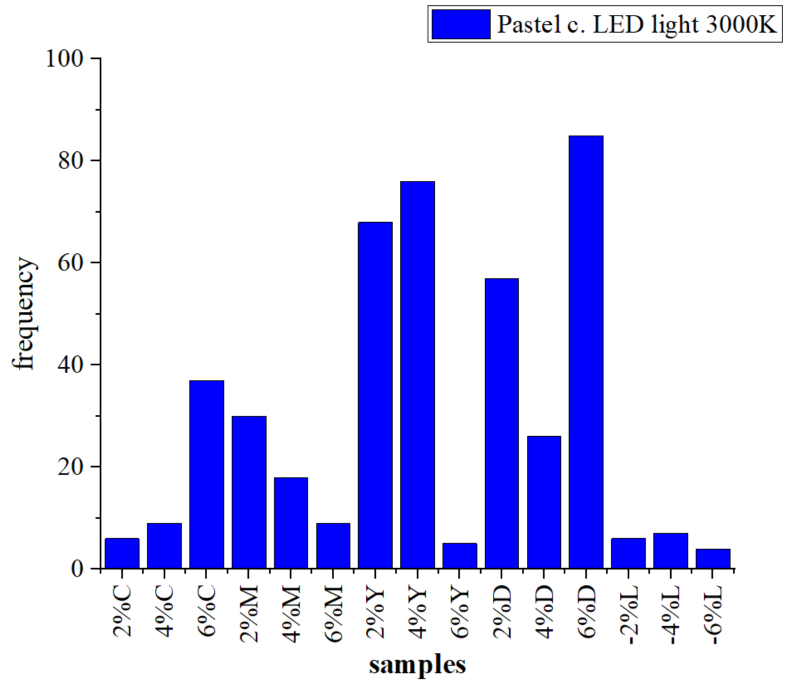


Figure 83. Description of the subjective evaluation of different samples of pastel colour under LED Light 3000K

Using the best Pastel colour painting samples under 3000K LED light the best comparison and matching were examined (Figure 84), according to the subjective findings.

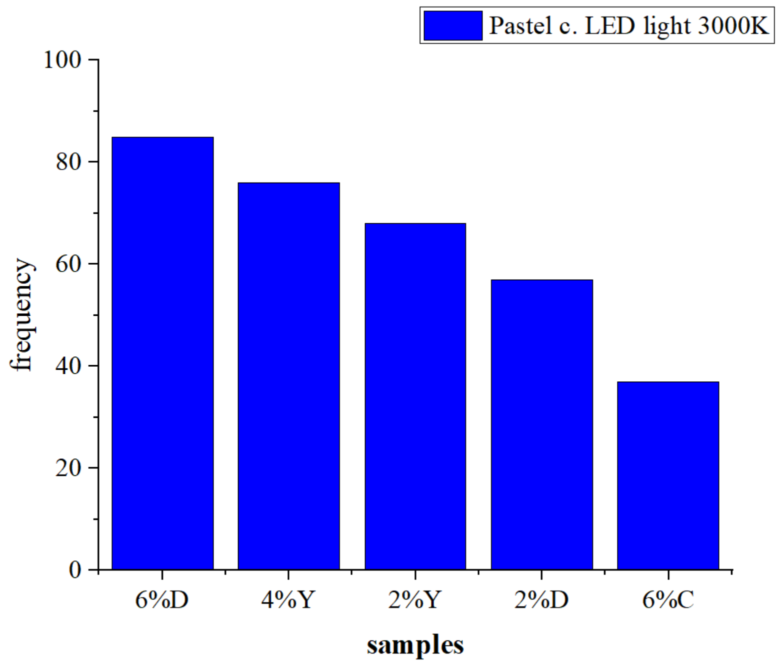


Figure 84. Best match samples of pastel colour under LED Light 3000K

Observers have classified a range of choices or nuances as shades with changes in the halftone, as shown by the study results in (Figure 84). The first subtlety with a deeper tone, 6%D, is placed after the colour with the highest percentages in terms of scoring, followed by the second sample, 4%Y, and the third sample, 2%Y. The fourth shade with a small percentage, 2%D, and the last nuance 6%C. Different lighting and colours each have their own distinct characteristics when we mix or modify one another.

All relevant nuances and their score according to the observer's individual decision on pastel colour under LED light 4000K, and according to the ranking are discussed in this way since the research entails assessing samples that were chosen based on how close they are to the original sample (Figure 85).

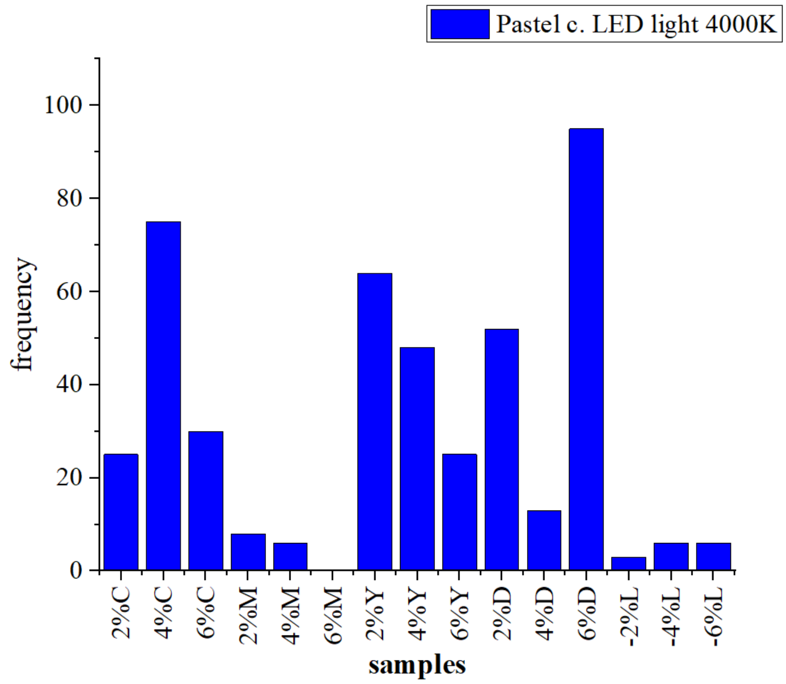


Figure 85. Description of the subjective evaluation of different samples of pastel colour under LED Light 4000K

According to subjective findings, the best comparison and matching were evaluated using the best pastel colour painting samples under LED light 4000K (Figure 86).

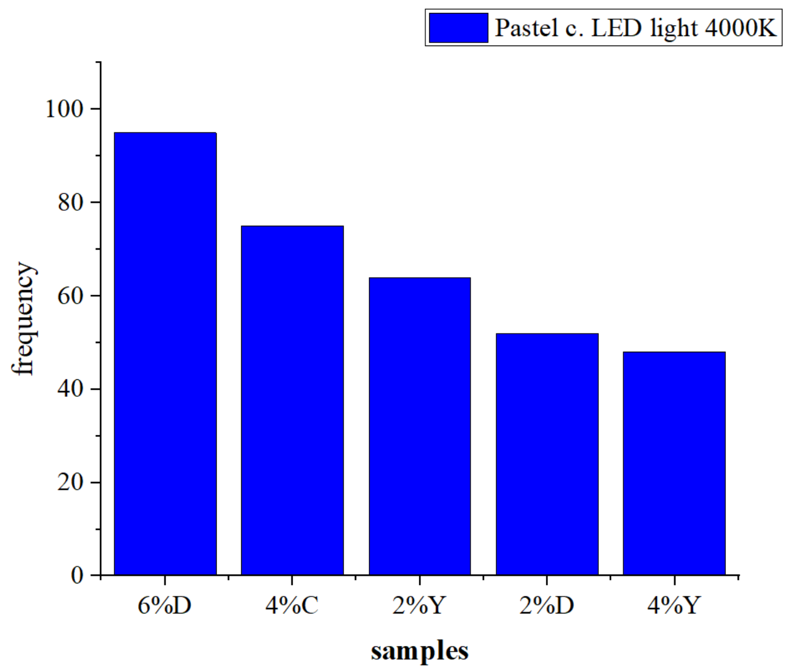


Figure 86. Best match samples of pastel colour under LED Light 4000K

According to the selection of the results closest to the original acrylic painting under LED Light 4000K at (Figure 86), it is demonstrated that the average evaluation by the observers is in the middle of half tone and mixed of half tone, from the best 6%D, the second 4%C, continuing with the third one 2%Y, the fourth sample 2%D, and the last one 4%Y.

To identify which samples, when viewed under LED Light 6500K (Figure 87), most closely resemble of the original pastel-colour artwork, all samples were subjectively assessed using the same methodology.

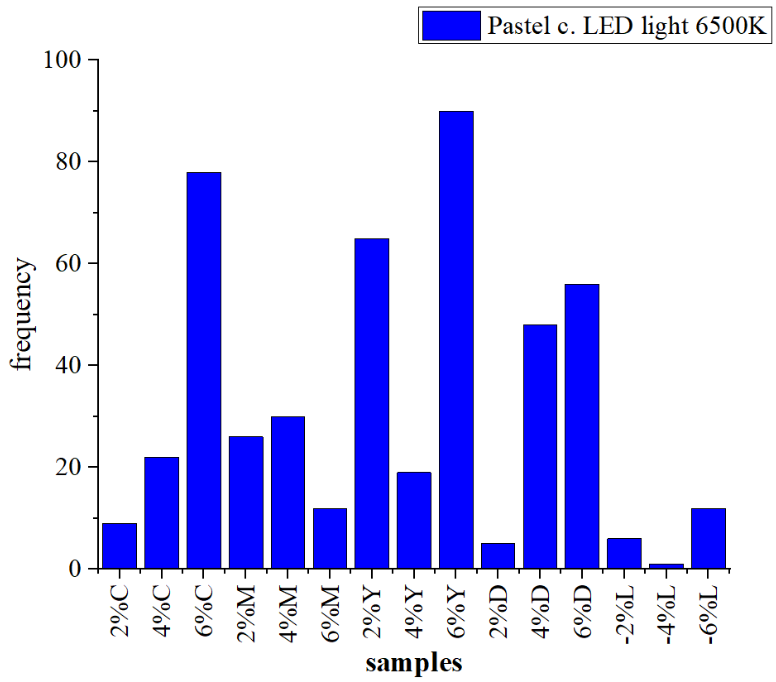


Figure 87. Description of the subjective evaluation of different samples of pastel colour under LED Light 6500K

According to the subjective results, the best comparison and matching was assessed using the best pastel colour painting samples under LED light 6500K (Figure 88).

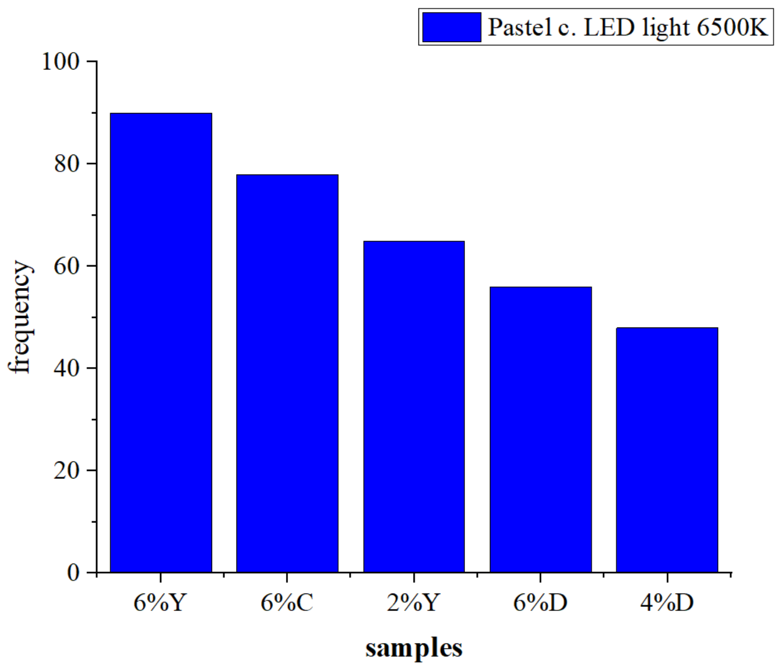


Figure 88. Best match in pastel colour under LED Light 6500K

It is shown (Figure 88), that the average assessment by the observers is in the centre of highest of half tone at, based on the selection of the results closest to the original Pastel colour painting under LED Light 6500K, it starts with highest yellow tone from the best 6%Y, second 6%C, by continuing with the third one 2%Y, the fourth sample 6%D, and final one 4%D. Many variations are duplicated in this experiment, but to varying degrees.

All samples were subjectively evaluated using the same method, the samples most closely resembled the original pastel-coloured artwork when seen under Wolfram light (Figure 89).

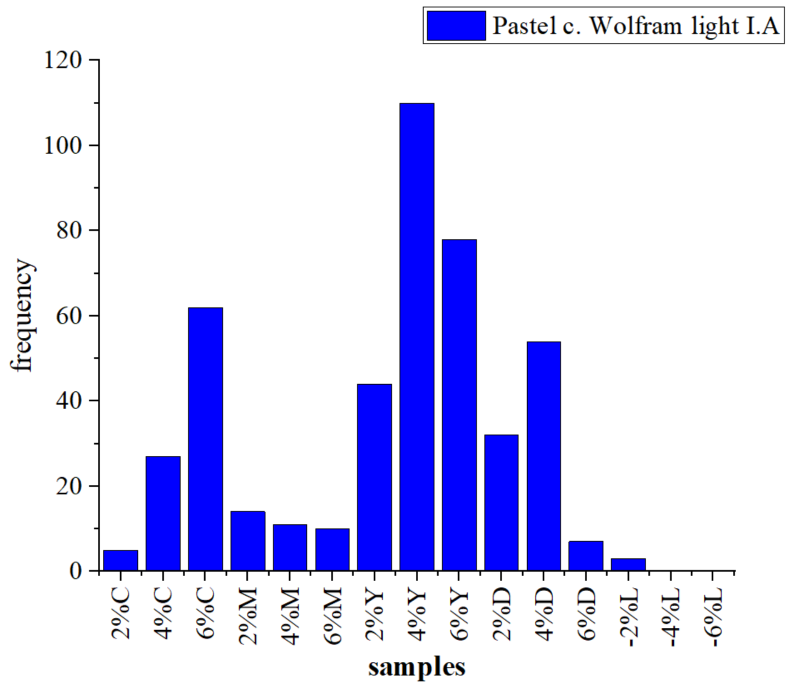


Figure 89. Description of the subjective evaluation of different samples of pastel colour under Wolfram Light

The best comparison and matching of subjective results (Figure 90) were assessed using the best pastel colour painting samples under Wolfram light.

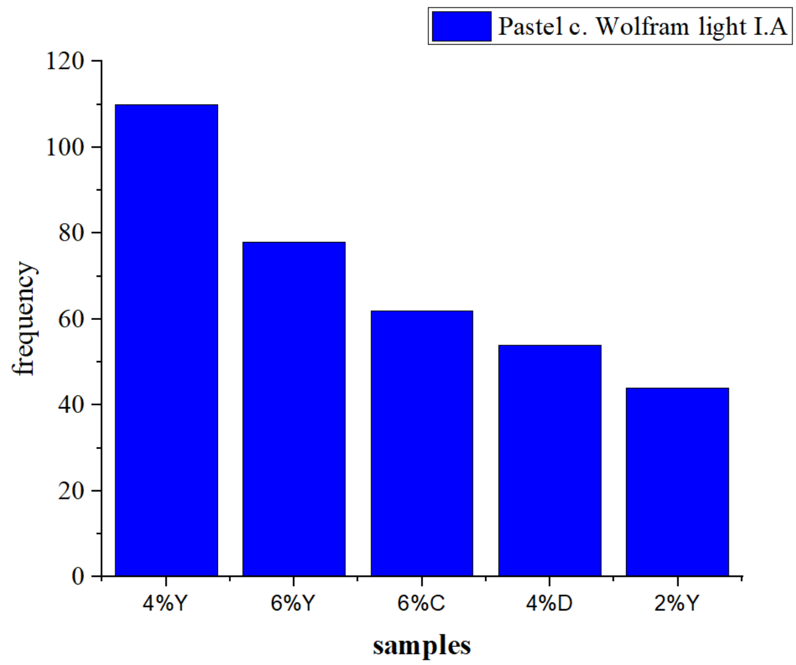


Figure 90. Best match samples of pastel colour under Wolfram Light

In the selections of the five closest to the original, in the Pastel colour technique under Wolfram Light (Figure 90), all shades of yellow are present, starting with the first selection 4%Y, the second 6%Y, the third different shade 6%C, the fourth-choice 4%D, and finally again closing with shade 2%Y.

Evaluation of the subjective description with all samples of Pastel colour under Halogen light (Figure 91).

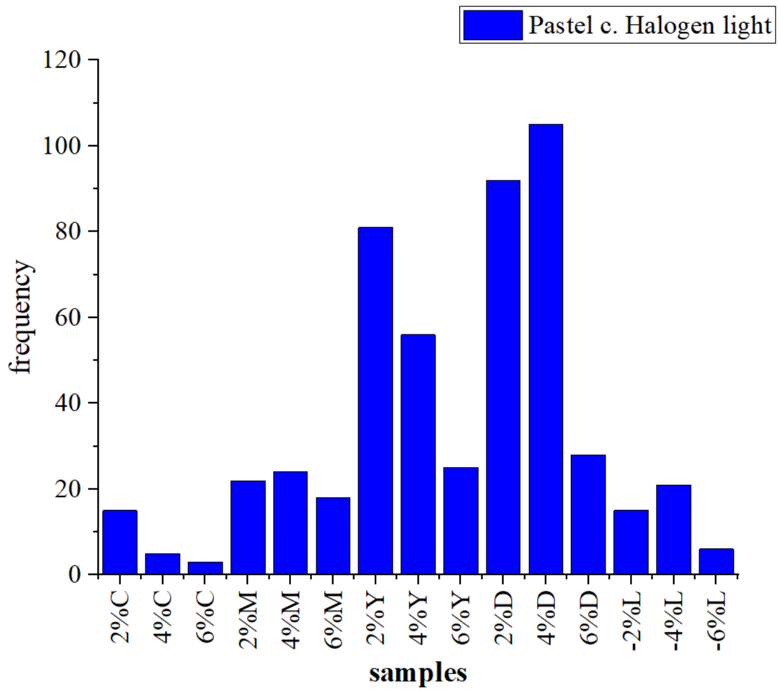


Figure 91. Description of the subjective evaluation with different samples of pastel colour under Halogen Light

The best pastel-colour painting samples under Halogen light were used to evaluate the comparison and matching of subjective outcomes (Figure 92).

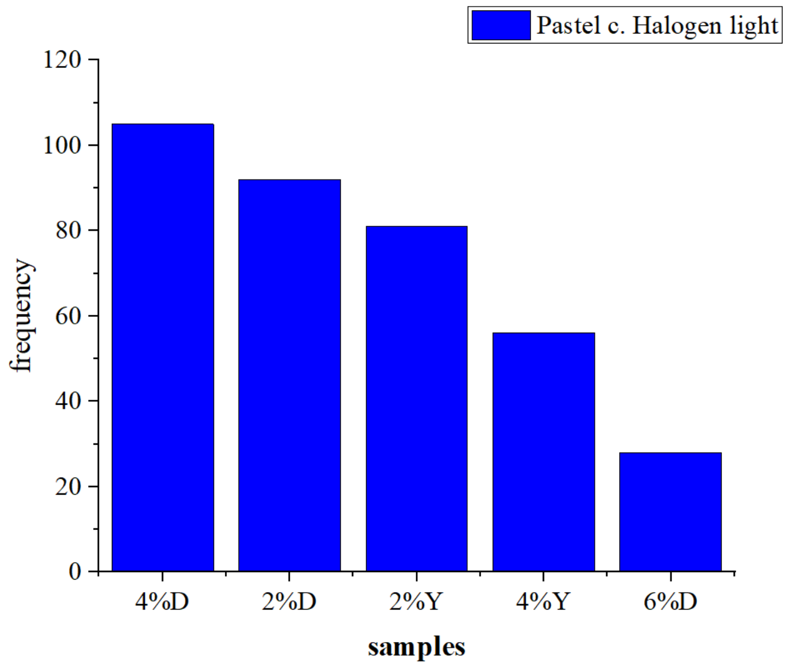


Figure 92. Best match samples of pastel colour under Halogen Light

In (Figure 93), which demonstrates that the average assessment by the observers reveals a lesser and mixed percentage of half tones are mainly picked, displays the findings that were chosen as being the closest to the original of pastel colour painting under Halogen Light.

All percentages of the +CMYK- (D) tone are present in this light, by starts with the best 4%D, followed by the second 2%D, the third best choice 2%Y, fourth 4%Y, and the highest tone the last one 6%D.

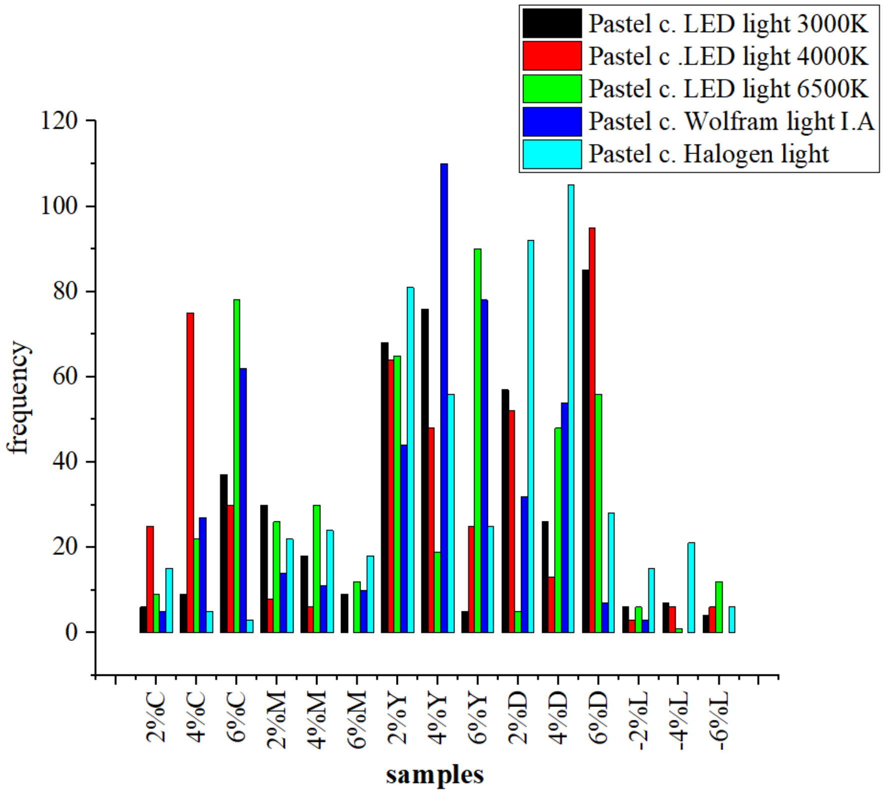


Figure 93. Description of the subjective evaluation of pastel colour samples under different light sources

In the analysis of the visual evaluations of the observers of the pastel painting and its samples (Figure 93), a mixture of the selection of half tones was achieved. In general, under the illumination of five different lights, the shades of magenta (M) and -CMYK (Lighter -L) are generally the least selected.

Description of the subjective results with all samples of water colour under the illumination of LED light 3000K (Figure 94).

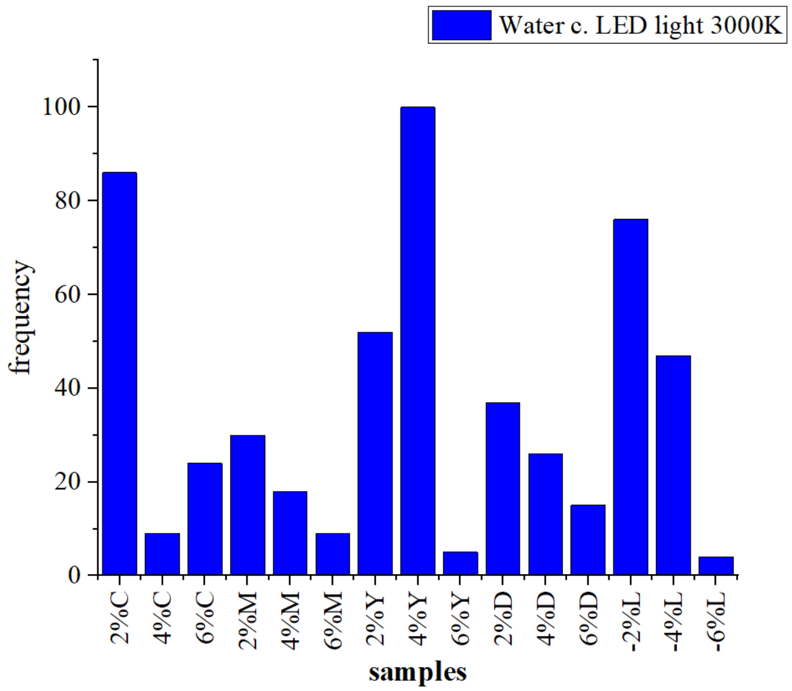


Figure 94. Description of the subjective evaluation with different samples of Water colour under LED Light 3000K

The best matching samples of subjective results (Figure 95) were evaluated by singing the water colour under LED light 3000K.

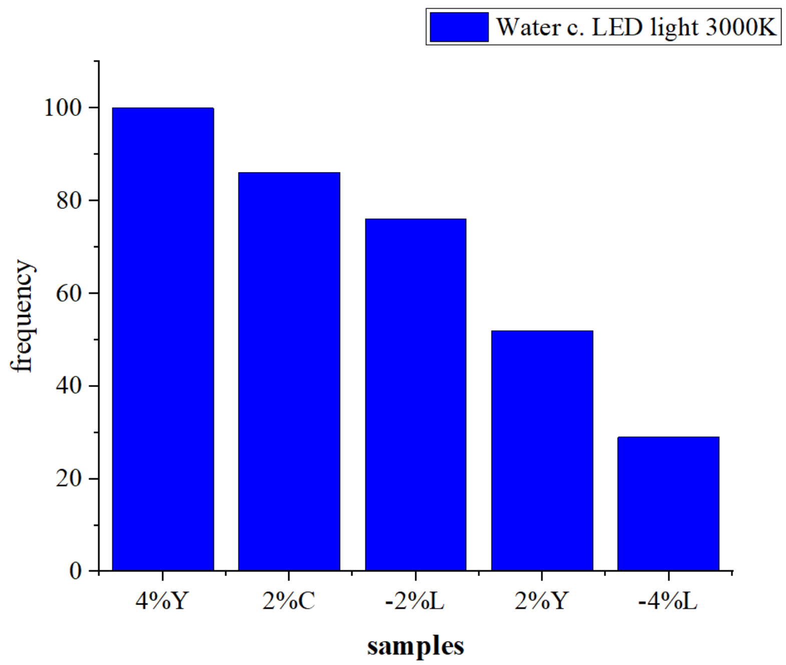


Figure 95. Best match samples of water colour under LED Light 3000K

Description of the five most selected water colour samples under illumination of Led light 3000K (Figure 95). In this approach of the technical type of colours and lighting, results with the percentage of 2% and 4% have been achieved. Selection of shades for lighter shades such as cyan, yellow lighter, and this can because the colour of the technical water gives a lighter appearance and does not absorb much light, also the observers under this test have selected the reproduction of the samples with a percentage of small.

The first choice is 4%Y, the second 2%C, the third -2%L, the fourth 2%Y, and the last -4%L. Description of subjective findings using all water colour samples under 4000K LED lighting (Figure 96). Here, the results of which samples are the most selected and which of the samples are the least selected under this light condition can be seen.

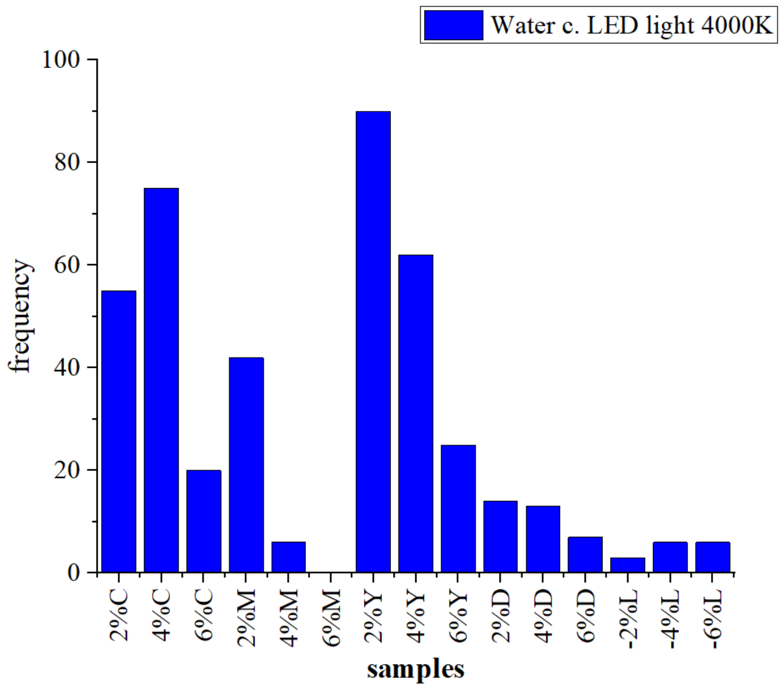


Figure 96. Description of the subjective evaluation with different samples of Water colour under LED Light 4000K

The five most visually selected samples by observers using the water colour technique under the illumination of LED light 4000K (Figure 97).

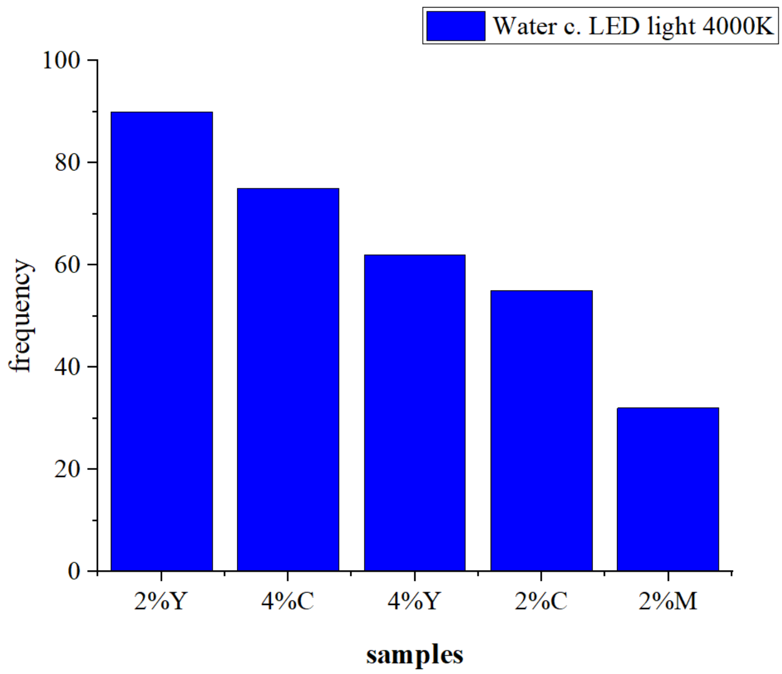


Figure 97. Best match samples of water colour under LED Light 4000K

The curation of watercolor results, characterized by the highest frequency counts under LED light of 4000K (Figure 97), is akin to the methodology employed for the selection of samples under LED light at 3000K. However, it should be noted that the sequencing differs. The selection process begins with the identification of the sample bearing the closest resemblance to the original, serving as the foundational reference point, denoted as 2%Y. Subsequently, the progression entails the inclusion of 4%C, 4%Y, another 2%Y, and culminates with 2%M, manifesting a sequential arrangement based on the degree of similarity to the original stimulus.

The comprehensive presentation of the watercolour test results, across all samples, in the context of LED Light 6500K illumination, is expounded upon through the subjective lens of observers (Figure 98). This holistic representation seeks to elucidate the collective perception and assessment of the watercolor specimens under the specific lighting conditions, shedding light on the qualitative aspects of these observations.

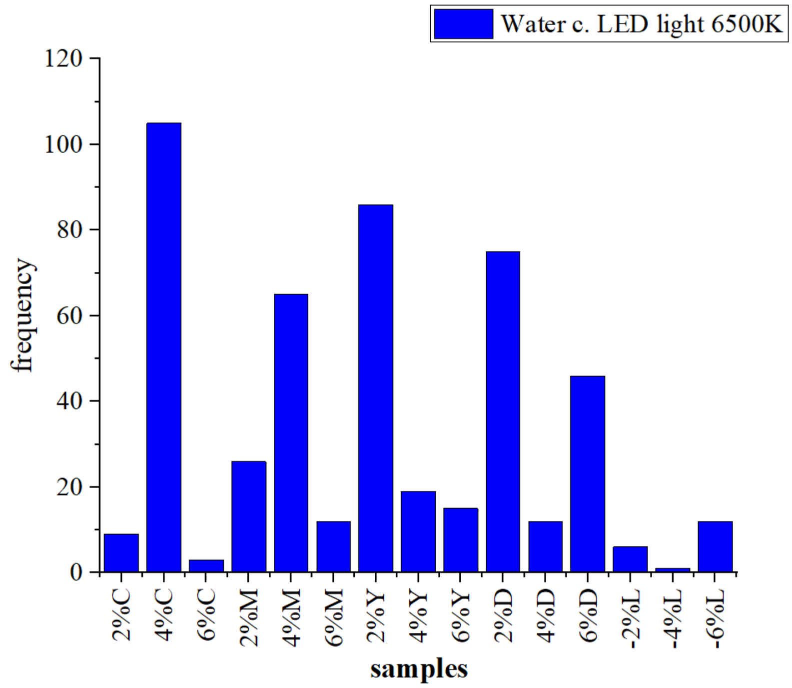


Figure 98. Description of the subjective evaluation with different samples of Water colour under LED Light 6500K

The most selected samples were selected in the subjective aspect of water colour under LED light 6500K (Figure 99).

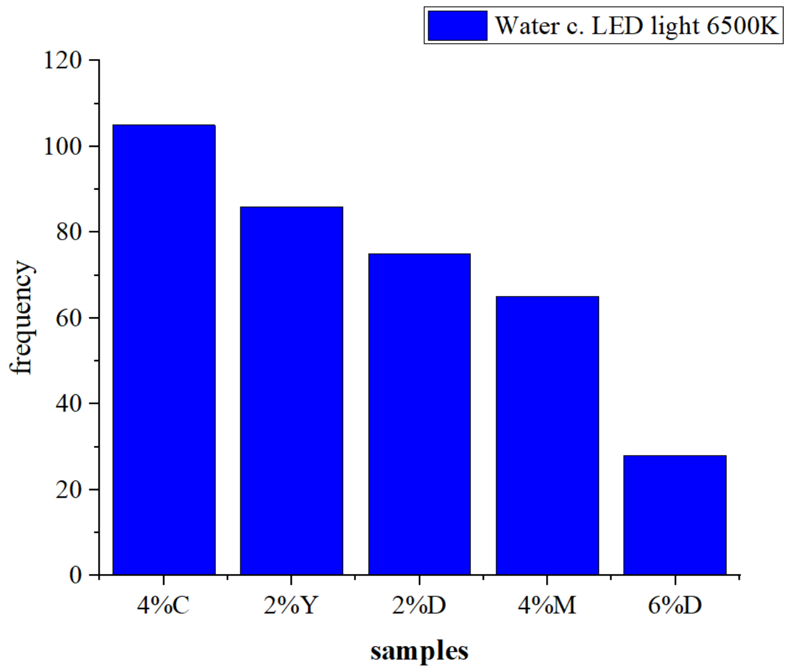


Figure 99. Best match samples of water colour under LED Light 6500K

In the selection of the five samples closest to the original of the water colour technique under the illumination of LED light 6500K (Figure 99), these mixed results were achieved, starting with the first one that the light may have influenced the selection of shades in blue 4%C, continued with 2%Y, 2%D, 4%M, and the last 6%D. It seems that observers no longer see many differences in different shades of colours.

Description of all the results of the sample used using the subjective evaluation with the water colour technique under Wolfram light (Figure 100).

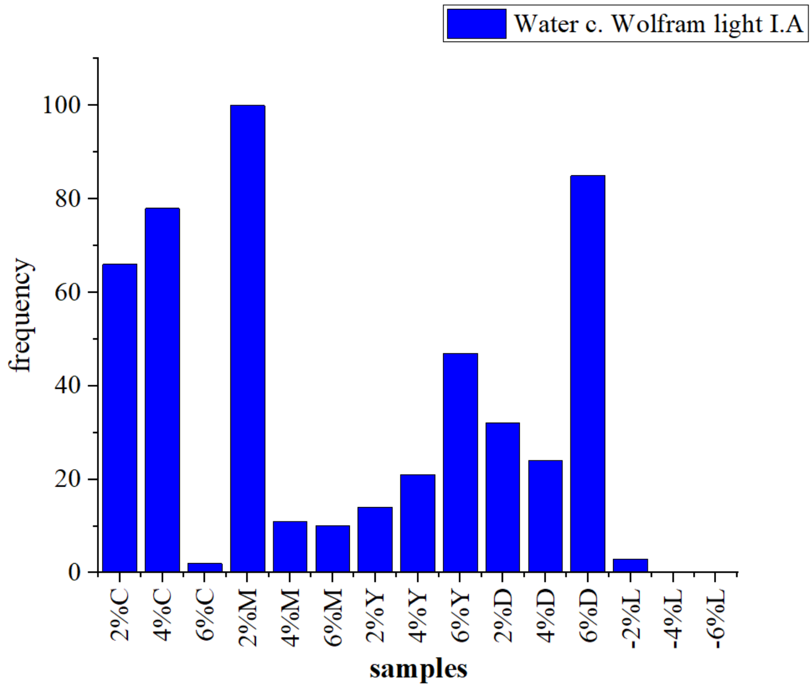


Figure 100. Description of the subjective evaluation with different samples of Water colour under Wolfram Light

The most selected samples subjectively of the water colour technique under Wolfram Light as it shown in (Figure 101).

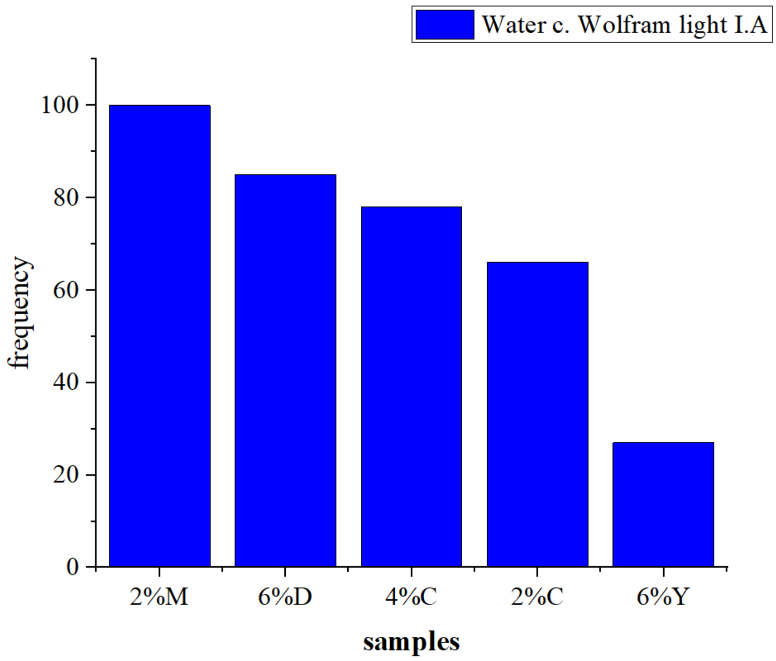


Figure 101. Best match samples of water colour under Wolfram Light

In the selection of most similar samples to the original water colour under the illumination of Wolfram light (Figure 101), the first choice as a reference to the original is the shade 2%M, where the observers were influenced by the colour temperature of light, more consistent with the other samples following like 6%D, 4%C, 2%C and the last 6%Y.

Subjective evaluation with different samples of water colour under Halogen light description, by comparing the most things one in each light how it affects in perception of colour as it shown in (Figure 102).

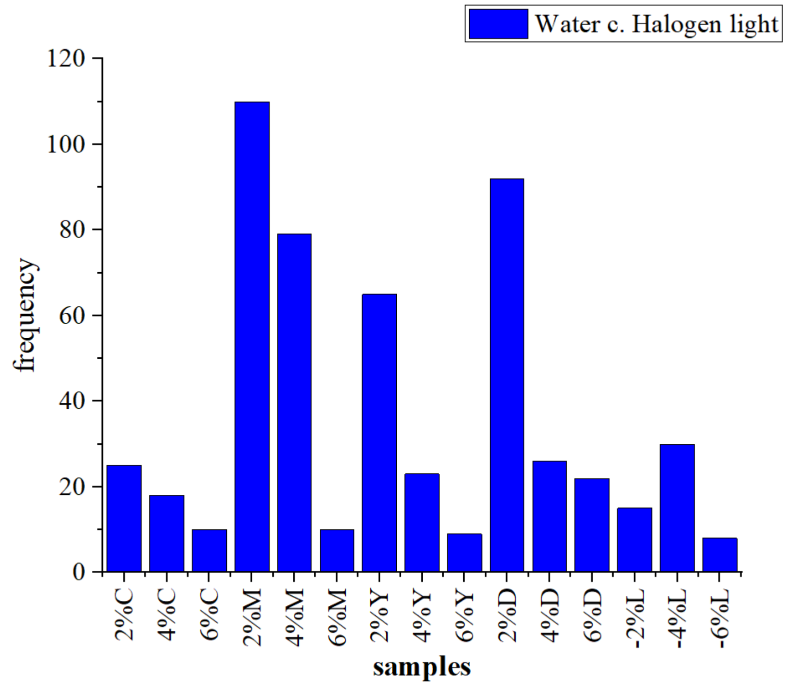


Figure 102. Description of the subjective evaluation with different samples of water colour under Halogen Light

The water colour best match samples chosen from observers under Halogen light as it shown in (Figure 103).

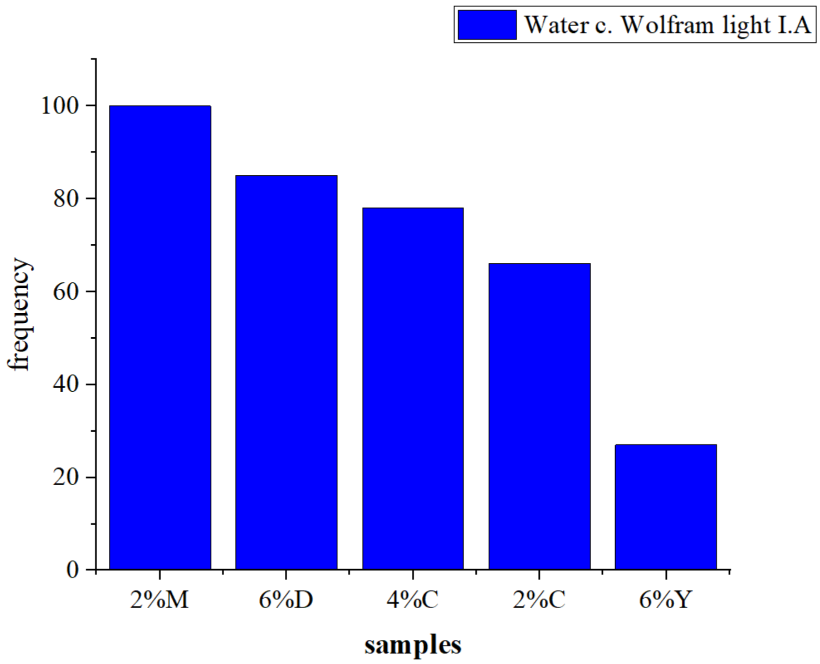


Figure 103. Best match samples of water colour under Halogen Light

In this comparison the most similar chosen samples to the original water colour under the halogen light (Figure 103), the first chosen one as reference to the original painting is the reproduction sample 2%M, which is the same tonality sample chosen under Wolfram light, this can be common while those two lights have similar specification in quality light.

Visual perception in humans can be triggered by quality in many aspects to choose more wisely. The other sample is a combination of smallest and middle tones that continues with 2%D, 4%M, 2%Y, and the last -4%L.

In the analysis of the visual evaluations of the observers on water colour samples (Figure 104), a mixture of the selection of half tones was achieved. In general, under the illumination of five different lights, the chosen shades are mixed.

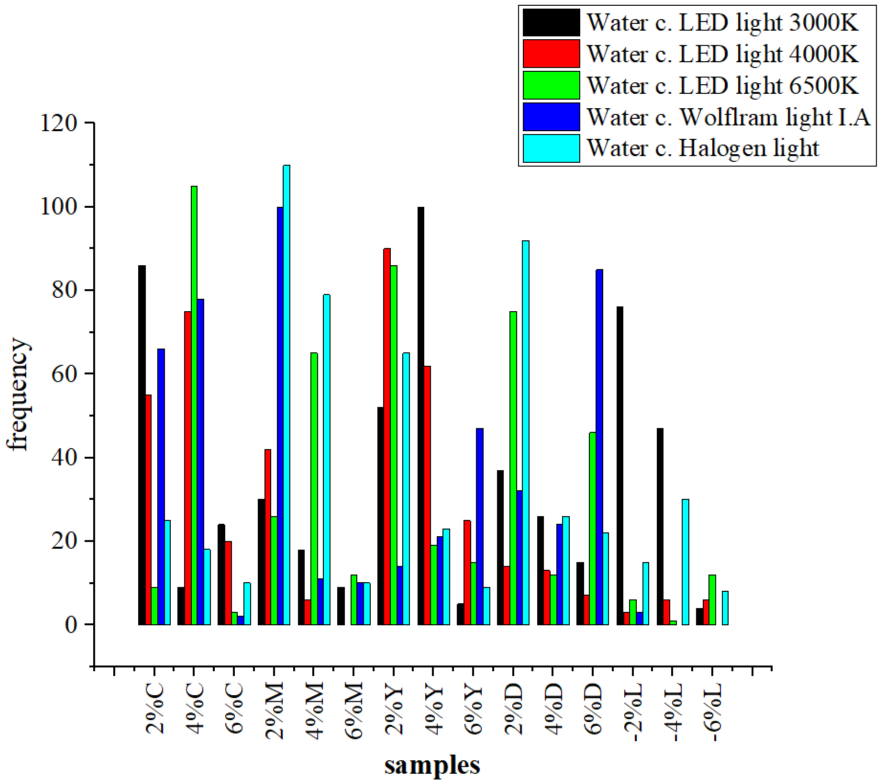


Figure 104. Description of the subjective evaluation of samples of water colour under different light sources

Spectrophotometric and densitometry measures were performed using the X-Rite eXact device (Figure 41), which is used for measurements in a wide gamut of different paper materials, films, sheets, and textiles. Conditions for measuring with a spectrophotometer are light D65 with e visual corner of 2’’, and when done by a densitometer, light A is used with the same visual corner. This device is used for measuring and controlling pressure in all sorts of special and conventional colours. In all cases, in order to achieve optimal accuracy, a white standard is integrated (reference point), which allows automatic calibration with not necessarily user intervention. Basic technical characteristics are shown in (Table 10).

Table 10. The basic technical characteristics of the device X-Rite eXact

Characteristics	**Value**
Wavelength range	400 – 700 nm
Measurement range	0 – 200% reflection
Measurement speed	2 s
Optical resolution	10nm
Geometry	45˚/ 0˚
Standard observer	2˚/ 10˚
Measuring surface	Ø1.5, Ø2, Ø4, Ø6 mm

X-Rite eXact enable densitometric values measures, colour capture, and spectrophotometric values (CIE L * a* b*), raising the raster element, reflectance of light, also many other possibilities (Figure 105).

Figure 105. Measuring device X-Rite eXact [208]

8.2 Objective results and discussions

8.3 Metamerism index of different colour techniques and samples under different light sources

The grey balance fields of sample reproductions were analysed and measured in 10 different spots directions with L*a*b* values in, to achieve wider results, then the average number of each colour were presented.

This research includes the changing of half tone colour images by measuring metamerism index of the best samples, as similar to the original paintings under different standardised light sources, and those of quality control of the tonalities, to present correlation, management of image appearance and deviation.

The search for defined fields by printing forms will be done by laboratory measures, colorimetric differences of tristimulus values of the reflected colours. Differences in colour nuances CMYK will be placed in the grey space on the left part of the printed samples.

In this paper the attention is focused on modification of illuminant metamerism, in perception of artistic paintings, in addition to printed samples of tonal changes, which are defined by the international standards, applying to define the quality of grey balance.

However, the grey balance field is one of the main parameters of printing quality where the L*a*b* values will be measured. By this, enabling the observers to choose the most similar visual perception to the original paintings, compared to the samples of different tonalities under the different illuminant effects. This enables us to get subjective results, then the counting of points was done by the selection, ranking from the best selection of the most similar to the original painting to less similar, being 5 samples with the best match of each painting under the 5 sorts of light sources. Values L*a*b* will be taken to these samples. The measured values in the L*a*b* colour space will be done in the way that each sample will be measured ten times in the grey space, with the aim of having more measures to achieve the closest number of the colour average. L*a*b* values of Tempera colour under LED light, the reference which was the best matched as original compared to the other four best samples. With this, the comparison and difference of the Metamerism index colours is achieved. As shown in the (Table 11), under LED Light 3000K metamerism index is very small between the original (O) - 2%L and the other samples, mostly the results are accountably acceptable, especially the comparison of (O) - 2%L – second 2%C induces DE = 1.66, DE ab = 0.22, and (O) - 2%L – fourth 4%D induce the DE = 1.61, DE ab = 1.20. While the other two results MI is higher in lightness L*.

Table 11. Tempera colour under LED Light 3000K- MI values of reference vs. samples

Tempero c. LED Light 3000K Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 2%L - second 2%C	57.93	-6.18	-14.59	59.77	-6.27	-14.79	1.66	0.22
O. 2%L - third 6%L	57.93	-6.18	-14.59	63.29	-5.35	-15.46	4.79	1.20
O. 2%L - forth 4%D	57.93	-6.18	-14.59	59.24	-5.23	-15.31	1.61	1.20
O. 2%L - fifth 4%L	57.93	-6.18	-14.59	59.94	-5.72	-16.18	2.11	1.66

In the (Table 12), of Tempera colour under LED Light 4000K, metamerism index is higher between the original - O. 2%M with the other samples, mostly the results unacceptable are between the comparison of O. 2%M - second 4%D induce DE 2000 = 12.20, and DE ab = 5.83. The MI of O.2%M - third -4%L induces the DE 2000 = 12.60, DE ab = 4.76. The MI between O. 2%M – fourth 4% C induce DE 2000 = 6.15 while DE ab = 2.15 is smaller compared to other results. The Metamerism index between O. 2%M – fifth 6%C induces DE 2000 = 10.87, and DE ab = 2.81. The results of MI under LED Light 4000K are higher in lightness L*, even in ab* values, excluding samples 4%C and 6%C on ab* values.

Table 12. Tempera colour under LED Light 4000K- MI values of reference vs. samples

Tempero c. LED Light 4000K Ref.vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 2%M - second 4%D	47.42	-10.20	-18.28	59.23	-5.19	-15.31	12.20	5.83
O. 2%M - third 4%L	47.42	-10.20	-18.28	59.96	-5.846	-16.35	12.60	4.76
O. 2%M - forth 4%C	47.42	-10.20	-18.28	53.45	-11.84	-19.67	6.15	2.15
O. 2%M - fifth 6%C	47.42	-10.20	-18.28	58.41	-8.24	-16.27	10.87	2.81

In (Table 13), of Tempera colour under LED Light 6500K, the metamerism index is higher between the original – O. - 6%L with the other samples, mostly the results that are unacceptable are between the comparison of O. -6%L - second 4%D induce DE 2000 = 12.20, and DE ab = 5.83. The MI of O. -6%L - third 4%L induces DE 2000 = 12.60, DE ab = 4.76. The MI between O. -6%L – fourth 4%C induce DE 2000 = 6.15 while DE ab = 2.15 is smaller compared to other results. Metamerism index between O. -6%L – fifth 6%C induce DE 2000 = 10.87, and

DE ab = 2.81. The results of MI under LED Light 4000K are higher in lightness L*, even in ab* values, excluding samples 4%C and 6%C on ab* values.

Table 13. Tempera colour under LED Light 6500K- MI values of reference vs. samples

Tempero c. LED Light 6500K Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 6%L - second 4%M	63.24	-5.22	-15.28	59.23	-5.19	-15.31	3.47	0.04
O. 6%L - third 6%D	63.24	-5.22	-15.28	59.96	-5.846	-16.35	2.92	1.24
O. 6%L - forth 2%M	63.24	-5.22	-15.28	53.45	-11.84	-19.67	10.28	7.94
O. 6%L - fifth 4%C	63.24	-5.22	-15.28	58.41	-8.24	-16.27	4.95	3.18

In (Table 14), of Tempera colour under Wolfram Light it is seen that MI is mismatching between the original - O. - 6%L with the other samples, the results unacceptable are between the comparison of O. - 6%L - second 4%M induce the DE 2000 = 13.33, and DE ab = 4.39. The MI of O. - 6%L - third 4%D it is decreased compared with other samples with results DE 2000 = 3.69, the smallest difference under this light source is at DE ab = 0.38. The MI between O. - 6%L – fourth 6%D induce DE 2000 = 9.37 while DE ab = 4.81. The last comparison is higher between O. - 6%L – fifth 4%C induce DE 2000 = 10.37, and DE ab = 7.91. The results of MI at Tempera colour under Wolfram light are higher in lightness L*, even in ab* values, excluding reference O. - 6%L - 4%D is in L* and mostly in ab* values.

Table 14. Tempera colour under Wolfram light - MI values of reference vs samples

Tempero c. Wolfram Light Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 6%L - second 4%M	63.24	-5.22	-15.28	49.13	-5.39	-19.67	13.33	4.39
O. 6%L - third 4%D	63.24	-5.22	-15.28	58.98	-5.447	-15.59	3.69	0.38
O. 6%L - forth 6%D	63.24	-5.22	-15.28	53.63	-7.08	-10.85	9.37	4.81
O. 6%L - fifth 4%C	63.24	-5.22	-15.28	53.44	-12.09	-19.20	10.37	7.91

In (Table 15), of Tempera colour under Halogen Light it is seen that MI is mismatching between the original O. 6%L with two other samples, the results are unacceptable between the comparison of O. - 2%L - second 2%M induce the DE 2000 = 10.89, and DE ab = 5.46. Also, the MI mismatch of O. - 2%L - fifth 4%M is higher comparing with other samples with the results achieved of DE 2000 = 8.87, at DE ab = 5.33. The accountably acceptable MI between O. - 2%L – third 4%D induce DE 2000 = 1.61, while DE ab = 1.20. The last comparison is the closest result between O. - 2%L – fourth 2%C induce DE 2000 = 1.66, and DE ab = 0.22. The results of MI at Tempera colour under Wolfram Light are mixed values, which are gain in two samples pleasurable results at MI.

Table 15. Tempera colour under Halogen Light - MI values of reference vs sample

Tempero c. Halogen Light Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 2%L - second 2%M	57.93	-6.18	-14.59	47.42	-10.20	-18.28	10.89	5.46
O. 2%L - third 4%D	57.93	-6.18	-14.59	59.24	-5.226	-15.31	1.61	1.20
O. 2%L - forth 2%C	57.93	-6.18	-14.59	59.77	-6.27	-14.79	1.66	0.22
O. 2%L - fifth 4%M	57.93	-6.18	-14.59	49.35	-5.21	-19.82	8.87	5.33

In (Table 16), of Oil colour under LED Light 3000K it is seen that MI is mismatching between the original - O. 4%C and other samples, the results of MI are mostly higher in Lightnes L*, between the comparison of O. 4%C - second 2%M induce DE 2000 = 7.22, and DE ab = 1.92. The MI mismatch of O.4%C - third 2%D it is higher in Lightness L* results achieved of DE 2000 = 12.15, while DE ab = 0.92 is the closest in hue to the original reference. The MI between O. 4%C – fourth 6%C induce DE 2000 = 5.46, while DE ab = 3.13. The last comparison shows the highest results of mismatch between O. 4%C – fifth 4%D induce DE 2000 = 13.57, and DE ab = 6.29. The results of MI at oil colour under LED Light 3000K are higher in mismatch, excluding in two comparison of hues that are at least acceptable.

Table 16. Oil colour under LED Light 3000K- MI values of reference vs samples

Oil c. LED Light 3000K Ref. vs Samples	**L***	**a***	**b***	**L*2**	**a*2**	**b*2**	**DE 2000**	**DE ab**
O. 4%C - second 2%M	56.67	-5.85	-16.74	49.34	-5.70	-18.65	7.22	1.92
O. 4%C - third 2%D	56.67	-5.85	-16.74	44.51	-5.544	-15.87	12.15	0.92
O. 4%C - forth 6%C	56.67	-5.85	-16.74	51.55	-8.79	-17.82	5.46	3.13
O. 4%C - fifth 4%D	56.67	-5.85	-16.74	43.64	-5.26	-10.47	13.57	6.29

In oil colour under LED light at 4000K (Table 17), the findings are typically greater in Lightnes L *, compared to other samples, indicating that the original reference O. 4%D and other samples are higher mismatched even in lightness L * and ab* values, excluding the reference O. The 4%D – fifth 6%M sample induces DE 2000 =2.65, and DE ab = 3.18, which makes the MI between those visible smaller than other results.

Table 17. Oil colour under LED Light 4000K- MI values of reference vs samples

Oil c. LED Light 4000K Ref. vs Samples	**L***	**a***	**b***	**L*2**	**a*2**	**b*2**	**DE 2000**	**DE ab**
O. 4%D - second 4%C	43.64	-5.26	-10.47	56.67	-5.85	-16.74	13.57	6.29
O. 4%D - third 2%C	43.64	-5.26	-10.47	55.53	-5.915	-18.81	12.86	8.37
O. 4%D - forth 4%Y	43.64	-5.26	-10.47	56.82	-3.73	-17.02	13.93	6.73
O. 4%D - fifth 6%M	43.64	-5.26	-10.47	45.44	-5.34	-13.65	2.65	3.18

In (Table 18), of Oil colour under LED Light 6500K it is seen that MI is mismatching between the original - O. 6%L with two other samples, the results of the most acceptable are between the comparison of reference O. 6%Y - second 2%Y induce DE 2000 = 1.77, and DE ab = 1.33. The other sample accountably acceptable match of MI is between O.6%Y and the fourth 4%Y with the results achieved of DE 2000 = 1.76, at DE ab = 2.68. The other two results are highly mismatched, especially in lightness L* values and different results in ab* values, which are more closely related to the original.

Table 18. Oil colour under LED Light 6500K- MI values of reference vs samples

Oil c. LED Light 6500K Ref.vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 6%Y - second 2%Y	57.74	-3.34	-14.37	59.31	-2.61	-15.48	1.77	1.33
O. 6%Y - third 2%D	57.74	-3.34	-14.37	44.51	-5.544	-15.87	13.35	2.67
O. 6%Y - forth 4%Y	57.74	-3.34	-14.37	56.82	-3.73	-17.02	1.76	2.68
O. 6%Y - fifth 6%D	57.74	-3.34	-14.37	43.23	-3.89	-10.21	14.77	4.20

In the analysis of oil colour (Table 19) under Wolfram Light, the findings of MI are typically greater in Lightness L* than in other samples, indicating that the original reference O. 6%C and other samples are higher mismatched even in lightness L * and ab* values, excluding the reference O. The 6% C - third 4%C sample induces DE 2000 = 5.46 and DE ab = 3.13, which is obviously smaller than other results.

Table 19. Oil colour under Wolfram Light- MI values of reference vs samples

Oil c. Wolfram Light Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 6%C - second 6%D	51.55	-8.79	-17.82	43.23	-3.89	-10.21	10.07	9.05
O. 6%C - third 4%C	51.55	-8.79	-17.82	56.67	-5.85	-16.74	5.46	3.13
O. 6%C - forth 2%D	51.55	-8.79	-17.82	44.51	-5.54	-15.87	7.48	3.79
O. 6%C - fifth 6%Y	51.55	-8.79	-17.82	57.74	-3.34	-14.37	7.65	6.45

In oil colour under Halogen light (Table 1.20), the findings of MI are typically greater in Lightness L *, compared to other samples, indicating that the original reference O. 2%M and other samples are mixed results mismatched even in lightness L * and ab* values, excluding the reference O.2%M – third 2%D DE 2000 = 4.95 and DE ab = 2.79. The other comparison O. The sample of 2%M – four 4%C is higher the DE 2000 =7.22, and DE ab = 1.92, where MI between ab* values is visible smaller than other results. Under Halogen Light the oil colour samples are mostly mismatch between the reference and samples.

Table 20. Oil colour under Halogen Light- MI values of reference vs samples

Oil c. Halogen Light Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 2%M - second 6%C	49.34	-5.70	-18.65	51.55	-8.79	-17.82	3.49	3.20
O. 2%M - third 2%D	49.34	-5.70	-18.65	44.51	-5.544	-15.87	4.95	2.79
O. 2%M - forth 4%C	49.34	-5.70	-18.65	56.67	-5.85	-16.74	7.22	1.92
O. 2%M - fifth 4%D	49.34	-5.70	-18.65	43.64	-5.26	-10.47	7.35	8.19

In (Table 21), of Acryl colour under LED Light 3000K, it is seen that MI is higher between the reference O. 2%M with all other samples. At this comparison of MI, the difference of DE 2000 is high in Lightness L*, but mostly in this case is higher than other comparison in DE ab* values. It is worth mentioning in the first comparison of reference O. 2%M – second 4%Y that visually they are the differences' most selected, but the results are the highest with results of DE 2000 = 7.78 and the highest mismatch metamerism index of mismatch is in DE ab = 12.75. This means that visually in Acryl colour observers no longer see much difference as it comes when measuring colours, where there are higher results.

Table 21. Acryl colour under LED Light 3000K- MI values of reference vs samples

Acryl c. LED Light 3000K Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O.2%M - second 4%Y	53.65	-10.54	-20.50	51.11	-7.46	-8.13	7.78	12.75
O. 2%M - third 2%D	53.65	-10.54	-20.50	58.24	-6.325	-15.10	5.84	6.85
O. 2%M - forth 6%C	53.65	-10.54	-20.50	51.93	-8.68	-9.65	6.49	11.01
O. 2%M - fifth 4%D	53.65	-10.54	-20.50	58.54	-7.20	-15.63	5.63	5.90

In Acryl colour under LED light at 4000K (Table 22), MI findings of MI are typically higher in both Lightness* and ab* values, in all comparisons between reference and samples, indicating that the original reference O. 4% C and other samples are higher mismatched. The highest difference results in the between reference O. 4%C – second 4%Y sample induces DE 2000 =7.43, and DE ab = 12.14, that MI between these is visible higher than other results. Under the LED Light 4000K the Acryl colour samples yield results higher in DE ab* rather than DE 2000, which means that objectively they are more differentiated at hue.

Table 22. Acryl colour under LED Light 4000K- MI values of reference vs samples

Acryl c. LED Light 4000K Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 4%C - second 4%Y	53.46	-11.77	-19.47	51.11	-7.46	-8.13	7.43	12.14
O. 4%C - third 2%C	53.46	-11.77	-19.47	58.54	-7.204	-15.63	6.01	5.97
O. 4%C - forth 2%Y	53.46	-11.77	-19.47	52.20	-7.36	-14.31	4.19	6.79
O. 4%C - fifth 6%M	53.46	-11.77	-19.47	53.21	-7.82	-13.43	4.11	7.22

In (Table 23), of Acryl colour under LED Light 6500K, it is seen that MI is mismatching between the original - O. 6%L with two other samples, the results of the most acceptable are between the comparison of reference O. 6%Y - second 2%Y induce DE 2000 = 1.77, and DE ab = 1.33. The other sample accountably acceptable match of MI is between O.6%Y and the fourth 4%Y with the results achieved of DE 2000 = 1.76, at DE ab = 2.68. The other two results are highly mismatching, especially in lightness L* values and different results in ab* values, which are more closely related to the original.

Table 23. Acryl colour under LED Light 6500K- MI values of reference vs samples

Acryl c. LED Light 6500K Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 2%M - second 2%L	53.65	-10.54	-20.50	53.21	-7.82	-13.43	4.12	7.57
O. 2%M - third 4%L	53.65	-10.54	-20.50	52.48	-8.095	-12.00	4.96	8.84
O. 2%M - forth 4%Y	53.65	-10.54	-20.50	51.11	-7.46	-8.13	7.78	12.75
O. 2%M - fifth 2%D	53.65	-10.54	-20.50	55.71	-6.73	-14.46	4.48	7.14

In (Table 24), of Acryl colour under Wolfram Light I-A, it is seen that MI is mismatching between the original - O. - 6%L with other samples, the results of the less unacceptable are between the comparison of reference O. - 6%L - second 2%M induce the DE 2000 = 3.02, and DE ab = 3.86. The other sample that is accountably acceptable to match MI is between O. -

6%L - fourth 6%D with the results achieved of DE 2000 = 5.84, while DE ab = 2.23. The other two results are highly mismatching, especially in lightness L* values and different results in ab* values, which are more closely related to the original.

Table 24. Acryl colour under Wolfram Light I-A- MI values of reference vs samples

Acryl c. Wolfram Light Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 6%L - second 2%M	57.62	-6.66	-10.60	53.65	-10.54	-20.50	3.02	3.86
O. 6%L - third 4%M	57.62	-6.66	-10.60	51.75	-8.96	-19.21	7.57	8.91
O. 6%L - forth 6%D	57.62	-6.66	-10.60	51.93	-8.68	-9.65	5.84	2.23
O. 6%L - fifth 6%M	57.62	-6.66	-10.60	51.62	-7.60	-15.48	6.45	4.97

The acrylic colour samples under Halogen Light I- A, comparing the reference with other best matching samples, the degree of MI (Table 25) is higher, in most of the cases in this calculation, DE ab* are higher than DE 2000, instead of the reference O. 2%M - fourth 4%M, the smallest result of DE 2000 = 2.20, and DE ab = 2.04. This result is the most consistent in this light by measuring the colorimetric values.

Table 25. Acryl colour under Halogen Light I-A- MI values of reference vs samples

Acryl c. Halogen Light Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 2%M - second 2%D	53.65	-10.54	-20.50	55.71	-6.73	-14.46	4.48	7.14
O. 2%M - third 2%C	53.65	-10.54	-20.50	58.54	-7.204	-15.63	5.63	5.90
O. 2%M - forth 4%M	53.65	-10.54	-20.50	51.75	-8.96	-19.21	2.20	2.04
O. 2%M - fifth 2%Y	53.65	-10.54	-20.50	52.20	-7.36	-14.31	4.09	6.96

The pastel colour best match samples under LED Light 3000K at (Figure 26), the colour difference between the reference and other best samples, it is obvious the metamerism is present. Some results are higher in lightness as comparison between O.6%D – second 4%Y the result of DE 2000 = 7.81 and the DE ab = 5.21. The other results are smaller than the first comparison, the most acceptable MI is reference O.6%D – fifth 6%C where DE 2000 = 1.54, and the DE ab = 2.15.

Table 26. Pastel colour under LED Light 3000K- MI values of reference vs samples

Pastel c. LED Light 3000K Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O.6%D - second 4%Y	60.62	-2.56	-15.48	53.58	-7.42	-17.36	7.81	5.21
O. 6%D - third 2%Y	60.62	-2.56	-15.48	63.97	-4.52	-17.39	3.48	2.74
O. 6%D - forth 2%C	60.62	-2.56	-15.48	58.49	-4.50	-10.63	4.34	5.22
O. 6%D - fifth 6%C	60.62	-2.56	-15.48	61.74	-2.39	-17.62	1.54	2.15

The pastel colour samples under LED Light 4000K, colorimetric measurements of reference with four other best samples (Table 27). In this calculation, the highest MI results are between reference O.6%D – second 4%C with DE 2000 = 6.57, and a bit increased in DE ab = 7.62. The other results are decreased in DE ab. The metamerism is present in this presentation; exceptionally some results are least acceptable between the reference O.6%D – third 2%Y at DE ab = 2.05.

Table 27. Pastel colour under LED Light 4000K- MI values of reference vs samples

Pastel c. LED Light 4000K Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 6%D - second 4%C	54.28	-5.35	-12.17	59.46	-4.54	-19.75	6.57	7.62
O. 6%D - third 2%Y	54.28	-5.35	-12.17	59.51	-3.395	-11.55	5.22	2.05
O. 6%D - forth 2%D	54.28	-5.35	-12.17	57.30	-4.43	-15.30	3.62	3.26
O. 6%D - fifth 4%Y	54.28	-5.35	-12.17	58.43	-4.54	-7.42	5.04	4.82

In pastel colour best samples under LED Light 6500K (Table 1.28), through comparative values and colour difference DE 2000. In this calculation between the reference O. 6%Y and the most selected samples, they are significantly higher than others in terms of colour tones. In particular, the colour difference of the reference O. 6%Y - second 6%C with DE 2000 = 7.02 while the highest in DE ab = 9.91, the other high metamerism is between O.6%Y - fifth 4%D, with the DE 2000 = 5.55, while the highest DE ab = 8.12.

Table 28. Pastel colour under LED Light 6500K- MI values of reference vs samples

Pastel c. LED Light 6500K Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 6%Y - second 6%C	59.02	-4.31	-8.61	55.38	-8.01	-17.81	7.02	9.91
O. 6%Y - third 2%Y	59.02	-4.31	-8.61	59.51	-3.395	-11.55	2.44	3.07
O. 6%Y - forth 6%D	59.02	-4.31	-8.61	54.28	-5.35	-12.17	5.03	3.71
O. 6%Y - fifth 4%D	59.02	-4.31	-8.61	59.32	-2.75	-16.58	5.55	8.12

In pastel colour best samples under Wolfram Light (Table 29), through the colorimetric measurements and the colour difference DE 2000 in this calculation between the references O. 4%Y - second 6%Y are the most selected are the most acceptable values within this apparent comparison with DE 2000 results. = 1.09 and DE ab = 1.21.
In addition to the others, the results are visible greater in DE 2000, while in colour tones in DE ab, the metamerism is higher increased outcomes.

Table 29. Pastel colour under Wolfram Light- MI values of reference vs. samples

Pastel c. Wolfram Light Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 4%Y - second 6%Y	58.43	-4.54	-7.42	59.02	-4.31	-8.61	1.09	1.21
O. 4%Y - third 6%C	58.43	-4.54	-7.42	55.38	-8.01	-17.81	7.38	10.95
O. 4%Y - forth 4%D	58.43	-4.54	-7.42	59.28	-2.78	-16.57	6.51	9.31
O. 4%Y - fifth 2%Y	58.43	-4.54	-7.42	59.51	-3.40	-11.55	3.47	4.28

The most preferred values in this apparent comparison with the findings of DE 2000 are the reference O.4%D - second 2%D, which are the best pastel colour samples under Halogen Light (Table 30), according to colorimetric measurements and the colour difference DE 2000 =2.68 and DE ab = 2.11. In addition to the others, DE 2000 shows greater results, while DE ab's colour tones show higher enhanced metamerism. Specially between the reference O.4%D – four 4%C with DE 2000 = 6.53, and the highest metamerism in hue DE ab =9.34

Table 30. Pastel colour under Halogen Light- MI values of reference vs samples

Pastel c. Halogen Light Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 4%D - second 2%D	59.32	-2.75	-16.58	57.30	-4.43	-15.30	2.68	2.11
O. 4%D - third 2%Y	59.32	-2.75	-16.58	59.51	-3.395	-11.55	3.19	5.08
O. 4%D - forth 4%C	59.32	-2.75	-16.58	58.43	-4.54	-7.42	6.53	9.34
O. 4%D - fifth 6%D	59.32	-2.75	-16.58	54.28	-5.35	-12.17	6.15	5.12

The best watercolour samples under LED Light 3000K at (Figure 31) are reference O.4%Y - fifth 4%L, according to colorimetric tests, and the colour difference between DE 2000 = 1.54 and DE ab = 2.15, respectively. These values are the most desired values in this apparent comparison with DE 2000 results. Together with the others, DE 2000 exhibits better outcomes, whereas DE ab's colour tones exhibit more improved metamerism. Specifically, between the highest metamerism between the reference O.4%Y - second %C with findings of DE 2000 = 7.81, and DE ab = 5.21.

Table 31. Watercolour under LED Light 3000K- MI values of reference vs samples

Water c. LED Light 3000K Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O.4%Y - second 2%C	60.62	-2.56	-15.48	53.58	-7.42	-17.36	7.81	5.21
O. 4%Y - third 2%L	60.62	-2.56	-15.48	63.97	-4.52	-17.39	3.48	2.74
O. 4%Y - forth 2%Y	60.62	-2.56	-15.48	58.49	-4.50	-10.63	4.34	5.22
O. 4%Y - fifth 4%L	60.62	-2.56	-15.48	61.74	-2.39	-17.62	1.54	2.15

The best pastel colour samples under Halogen Light in (Figure 32), were chosen from observers, the reference O.2%M and other samples according to colorimetric tests, and the colour difference between DE 2000 and DE ab, is higher metamerism. These values are the most desired in this comparison with DE 2000 results. The colour difference results from this comparison in hue DE ab are much higher than the DE 2000 and lightness in general. Together with the others, DE 2000 exhibits better outcomes, while DE ab colour tones exhibit more improved metamerism. Specifically, between the maximum metamerism in the hue DE ab = 9.34 and the reference O.4%D - four 4%C with findings of DE 2000 = 6.53.

Table 32. Watercolour under LED Light 4000K- MI values of reference vs samples

Water c. LED Light 4000K Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 2%Y - second 4%C	58.49	-4.50	-10.63	54.60	-6.04	-16.72	5.24	6.28
O. 2%Y - third 4%Y	58.49	-4.50	-10.63	60.67	-2.564	-15.48	4.36	5.22
O. 2%Y - forth 2%C	58.49	-4.50	-10.63	53.58	-7.42	-17.50	6.50	7.46
O. 2%Y - fifth 2%M	58.49	-4.50	-10.63	58.38	0.28	-15.39	6.39	6.74

The water colour best samples under LED Light 6500K according to colorimetric values and colour differences DE 2000, the comparison of reference O.4%C with other best samples as the closest to original painting (Table 33), the results are mixed in lightness and some higher in hue comparison. The most acceptable comparison is between references O. 4%C – third 2%D DE 2000 = 2.95, and DE ab = 1.77.

Table 33. Watercolour under LED Light 6500K- MI values of reference vs samples

Water c. LED Light 6500K Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 4%C - second 2%Y	54.60	-6.04	-16.72	58.49	-4.50	-10.63	5.24	6.28
O. 4%C - third 2%D	54.60	-6.04	-16.72	57.27	-4.3	-16.42	2.95	1.77
O. 4%C - forth 4%M	54.60	-6.04	-16.72	59.92	-1.81	-18.09	6.50	4.45
O. 4%C - fifth 6%D	54.60	-6.04	-16.72	53.79	-5.33	-11.66	3.12	5.11

The findings are higher in terms of brightness and hue when comparing the watercolour best samples under Wolfram Light according to colorimetric values and colour differences DE 2000. Reference O.2%M with other best samples of the most similar to the original artwork as it shown in (Table 34). This section contains more instances of metamerism. The highest colour difference is between the reference O.2%M – fifth 6%Y with the DE 2000 = 7.53, and DE ab = 9.08.

Table 34. Watercolour under Wolfram Light- MI values of reference vs samples

Water c. Wolfram Light Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 2%M - second 6%D	58.38	0.28	-15.39	53.79	-5.33	-11.66	8.07	6.74
O. 2%M - third 4%C	58.38	0.28	-15.39	54.60	-6.04	-16.72	7.24	6.45
O. 2%M - forth 2%C	58.38	0.28	-15.39	53.58	-7.42	-17.50	8.59	7.98
O. 2%M - fifth 6%Y	58.38	0.28	-15.39	58.15	-4.03	-7.39	7.53	9.08

According to colorimetric values and colour differences DE 2000, the outcomes are greater when comparing the watercolour best samples under Halogen Light in terms of lightness and hue. Reference O.2%M with the best examples that closely resemble the original artwork (Table 35). Further metamerism can be found in this area. The reference sample O.2%M – four 2%Y has the biggest colour difference, with values of DE 2000 = 6.39 and DE ab = 6.74. The reference O.2%M it has mismatch metamerism when it comes to compare under the Wolfram light.

Table 35. Watercolour under Halogen Light- MI values of reference vs samples

Water c. Halogen Light Ref. vs Samples	L*	a*	b*	L*2	a*2	b*2	DE 2000	DE ab
O. 2%M - second 2%D	58.38	0.28	-15.39	57.27	-4.30	-16.42	4.94	4.69
O. 2%M - third 4%M	58.38	0.28	-15.39	59.92	-1.807	-18.09	2.85	3.41
O. 2%M - forth 2%Y	58.38	0.28	-15.39	58.49	-4.50	-10.63	6.39	6.74
O. 2%M - fifth 4%L	58.38	0.28	-15.39	61.74	-2.39	-17.62	4.18	3.48

8.3 Quality measurements of light sources with Colour Rendition ANSI/IES TM-30-18

8.3.1 The measuring of LED light 3000K with Colour Rendition TM-30-18

This research was done to obtain the most accurate measurement of lighting and colour evaluation, considering the visual presentation that includes highly saturated and unique colours, resulting in a more accurate representation of how colours appear under different light sources. In the TM-30 18 standard, the performance of the light sources is assessed using 99 colour samples. TM-30-18 addresses this issue by including specific colour evaluation metrics that are more suitable for LED sources. All light sources that are used in this research exhibit high colour fidelity in the TM-30 standard. At (Figure 106) the LED Light 3000K exhibits a high-quality lighting, a) Radiant power of the reference illuminant (black line) and the test illuminant (red line), b) local chroma shift, c) colour vector graphics (CVGs), d) local hue shifts, of the light output, and e) colour fidelity shift, which is the shift of 16 hue bins compared to the reference illuminant. As evident in radiant power changes between 630nm- 780nm, c) at CVGs, with rendering fidelity Rf-95, rendering gamut Rg-104, except for a little increase of CCT-3102K from the Kelvin indicated in technical specifications. The Duv a measure of the CCT value shift from the black body is -0.0061. In (b) are seen some increased percentage of local chroma shift is seen, while in (d) are decreased local hue shift from -0.02 to 0.04. Even though a high CRI Rf 95 in (e) the R6, R7, R8, R10 values are still below 95.

8.3.2 The measuring of LED Light 4000K with Colour Rendition TM-30-18

As evident below in (Figure 107), under LED Light 4000K exhibit high-quality lighting, the a) Radiant power is seen increasing between 630nm – 680nm, at (b,d) a small percentage of increasing and decreasing of local hue and chroma shift, c) colour vector graphics (CVGs), with Rendering fidelity Rf-96, Rendering gamut Rg-100, increased CCT- 4100K from the Kelvin indicated in technical specifications. The Duv measure of the shift in CCT value from the black body is -0.0015. Although a high CRI Rf 96 in (e) the R10, R11, R12 values are still below 95.

8.3.3 The Measuring of LED Light 6500K with Colour Rendition TM-30-18

Artificial light varies from each light even though many inventions are made close to day light, but there are always some differences in between. In (Figure108), LED Light 6500K the Radiant power (a) is seen increased and decreased between 430 nm - 580 nm, in (b,d) they are different percentages of the expanding and reducing of local hue and chroma shift compared to other lights, c) colour vector graphics (CVG), under LED Light 6500K exhibit a high quality lighting, with Rendering fidelity Rf-93, Rendering gamut Rg-100, CCT- 6500K as indicated in technical specifications. The Duv measure of the CCT value shift from the black body is 0.0050. This light shows that Rf is below 95, at (e) they are many mixed results, some are lower Rf 95 as R5, R10, R11, the lowest between those is R15- Rf 85. Higher than the light Rf are many, but is it worth to mention the highest R2, R7, R16.

8.3.4 The Measuring of Wolfram Light – I.A with Colour Rendition TM-30-18

As seen in below (Figure 109), the measurement of Wolfram light - Illuminant A, a) Radiant power is seen in one line the reference with test light, at (b,d) the local hue and chroma shift are 0% different from the reference, c) colour vector graphics (CVGs), exhibit the highest quality lighting, with Rendering fidelity Rf-100, Rendering gamut Rg-100, CCT- 2855K as indicated a little increased from technical specifications. The Duv measure of the CCT value shift from the black body is 0.0000. While Rf is 100, all in e) local colour fidelity from R1-R16, the results are 100. It shows a very qualitative light with the highest CRI.

8.3.5 The Measuring of Halogen Light with Colour Rendition TM-30-18

As shown in the (Figure 110), Halogen light, a) Radiant power is seen in one line the reference with test light, instead a tiny difference between 740nm – 780nm in (b, d) the local hue and chroma shift are 0% different from the reference, c) colour vector graphics (CVGs), exhibit the highest quality lighting, with Rendering fidelity Rf-100, Rendering gamut Rg-100, CCT-2654K as indicated a little decreased from technical specifications. The Duv a measure of the CCT value shift from the black body is 0.0003. All the findings from R1 to R16 for the e) Local colour fidelity is 100 when Rf is 100. It displays the highest CRI and extremely good quality light.

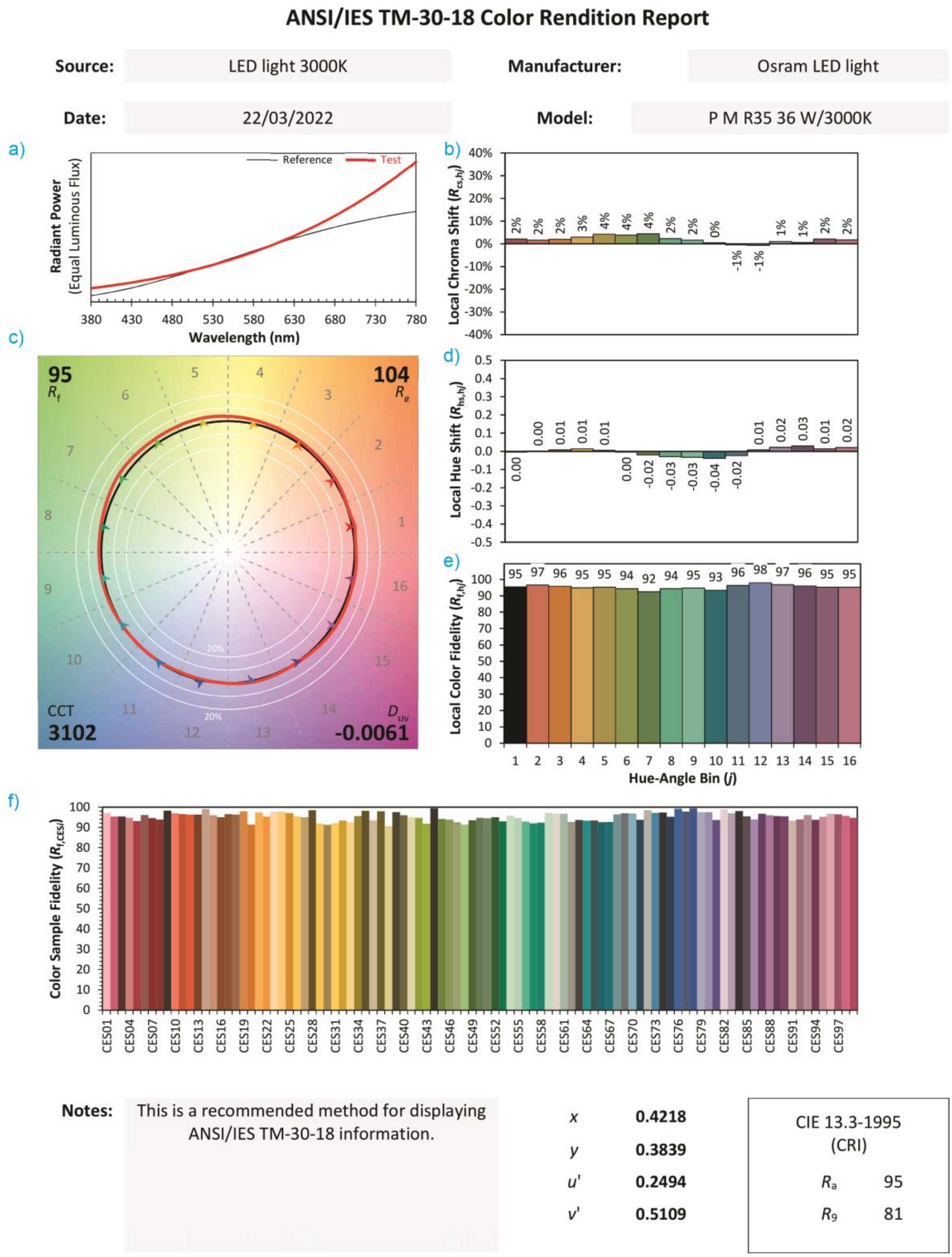


Figure 106. Measuring of LED Light 3000K a) Radiant power, b) Local chroma shift, c) TM-30-18 colour vector (CVGs), d) Local Hue shift, e) Local Color Fidelity, f) 99 Colour Samples

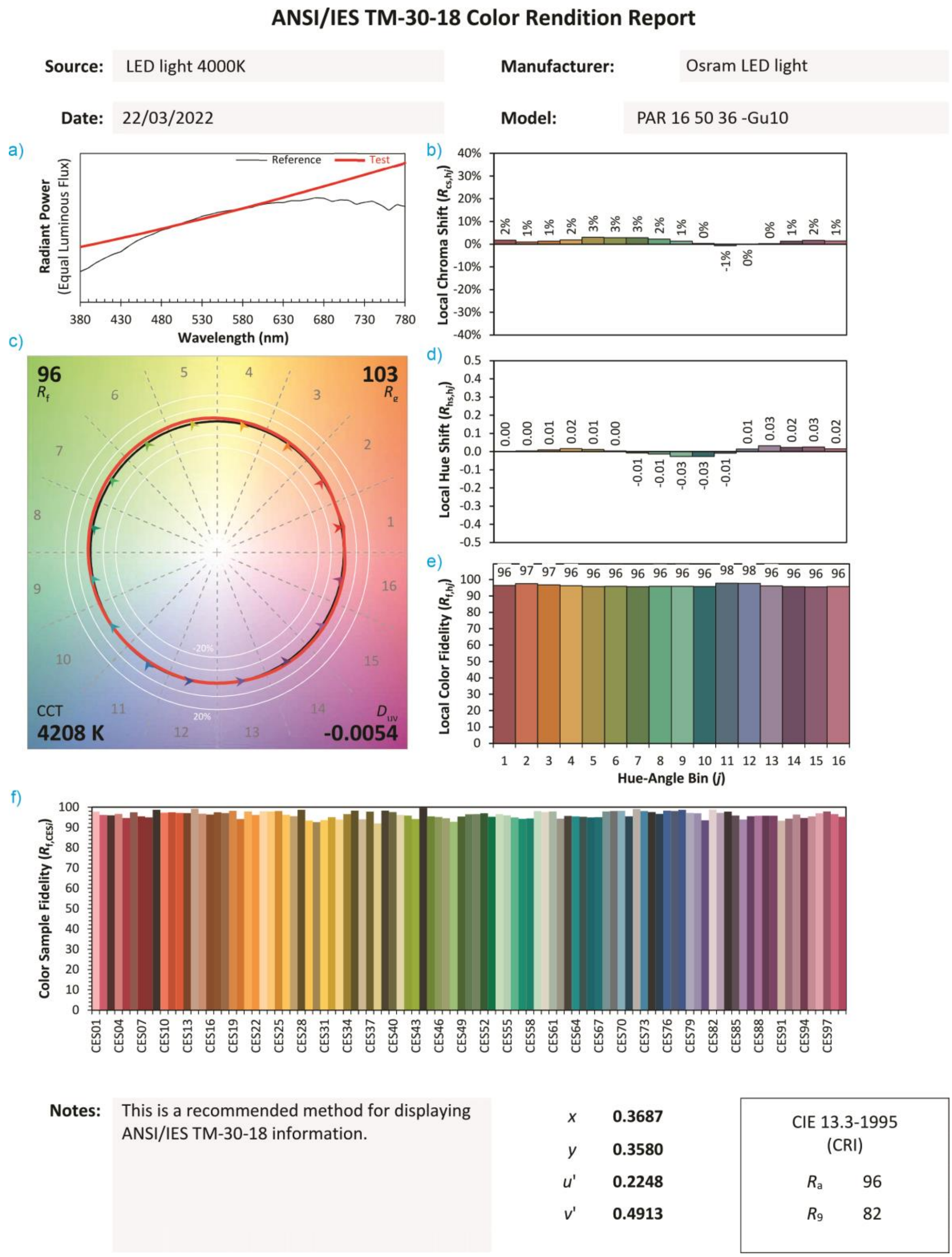


Figure 107. Measuring of LED Light 4000K a) Radiant power, b) Local chroma shift, c) TM-30-18 colour vector (CVGs), d) Local Hue shift, e) Local Color Fidelity, f) 99 Colour Samples

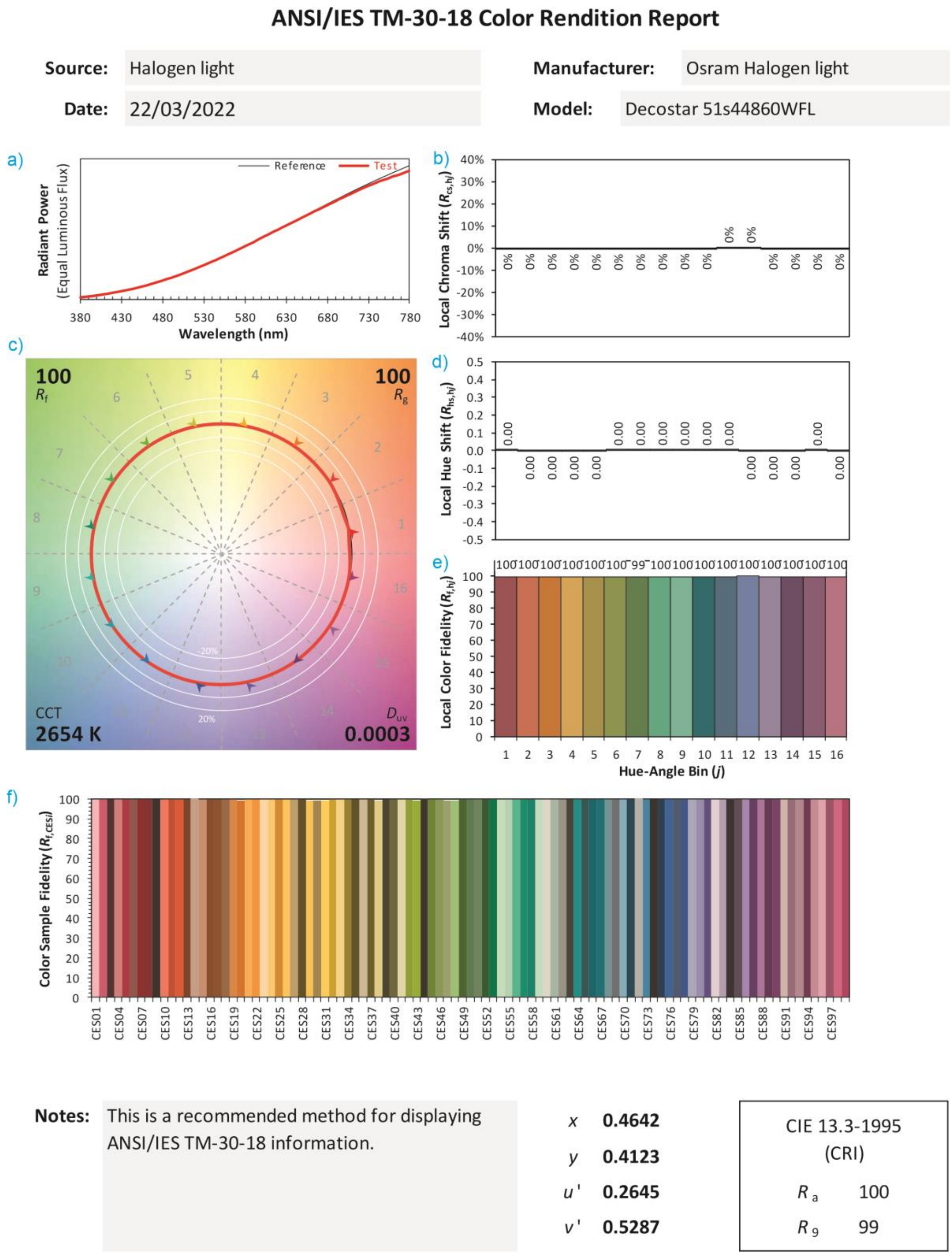


Figure 108. Measuring of LED Light 6500K a) Radiant power, b) Local chroma shift, c) TM-30-18 colour vector (CVGs)of LED Light 6500K, d) Local Hue shift, e) Local Color Fidelity, f) 99 Colour Samples

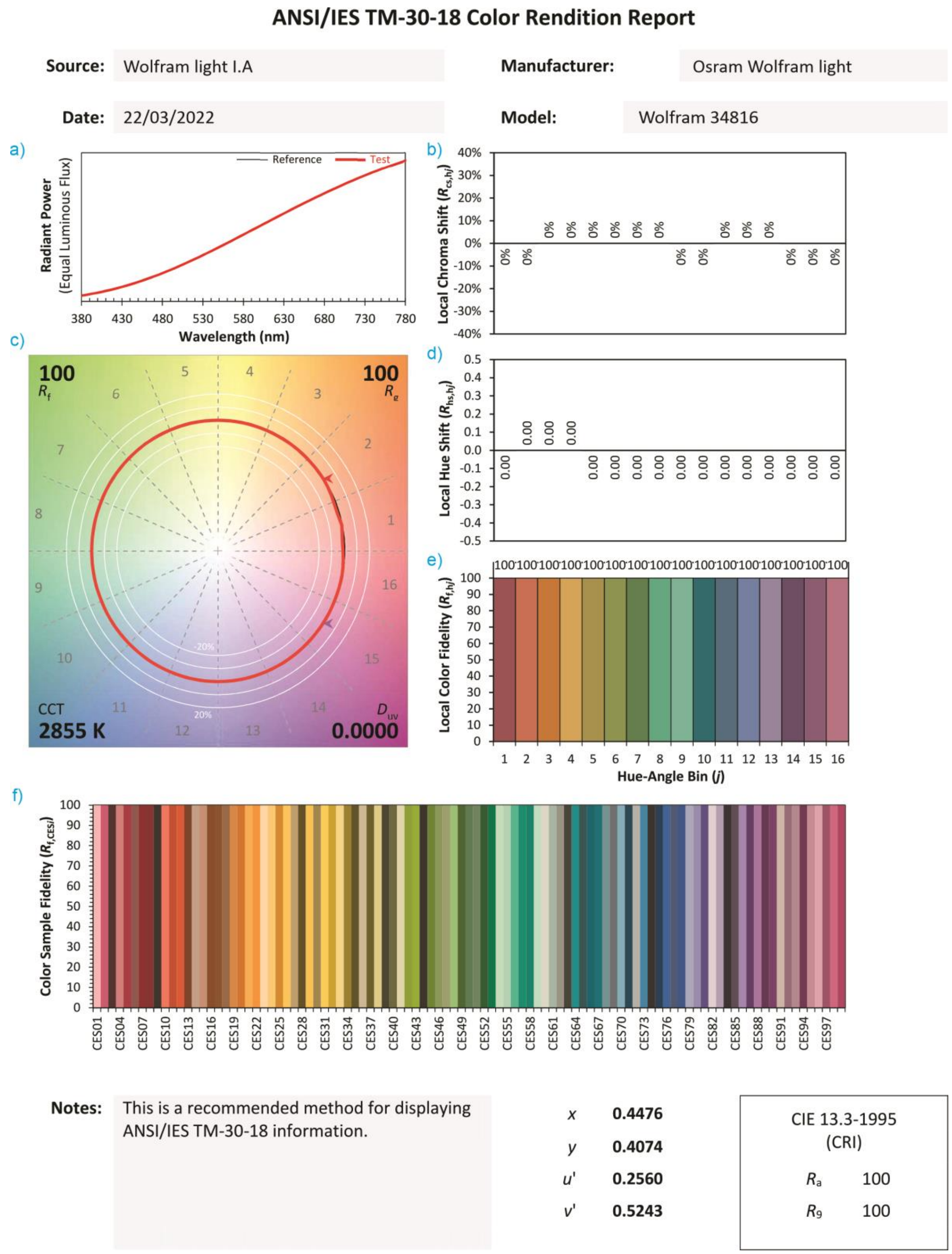


Figure 109. Measuring of Wolfram light, a) Radiant power, b) Local chroma shift, c) TM-30-18 colour vector (CVGs)of LED Light 6500K, d) Local Hue shift, e) Local Color Fidelity, f) 99 Colour Samples

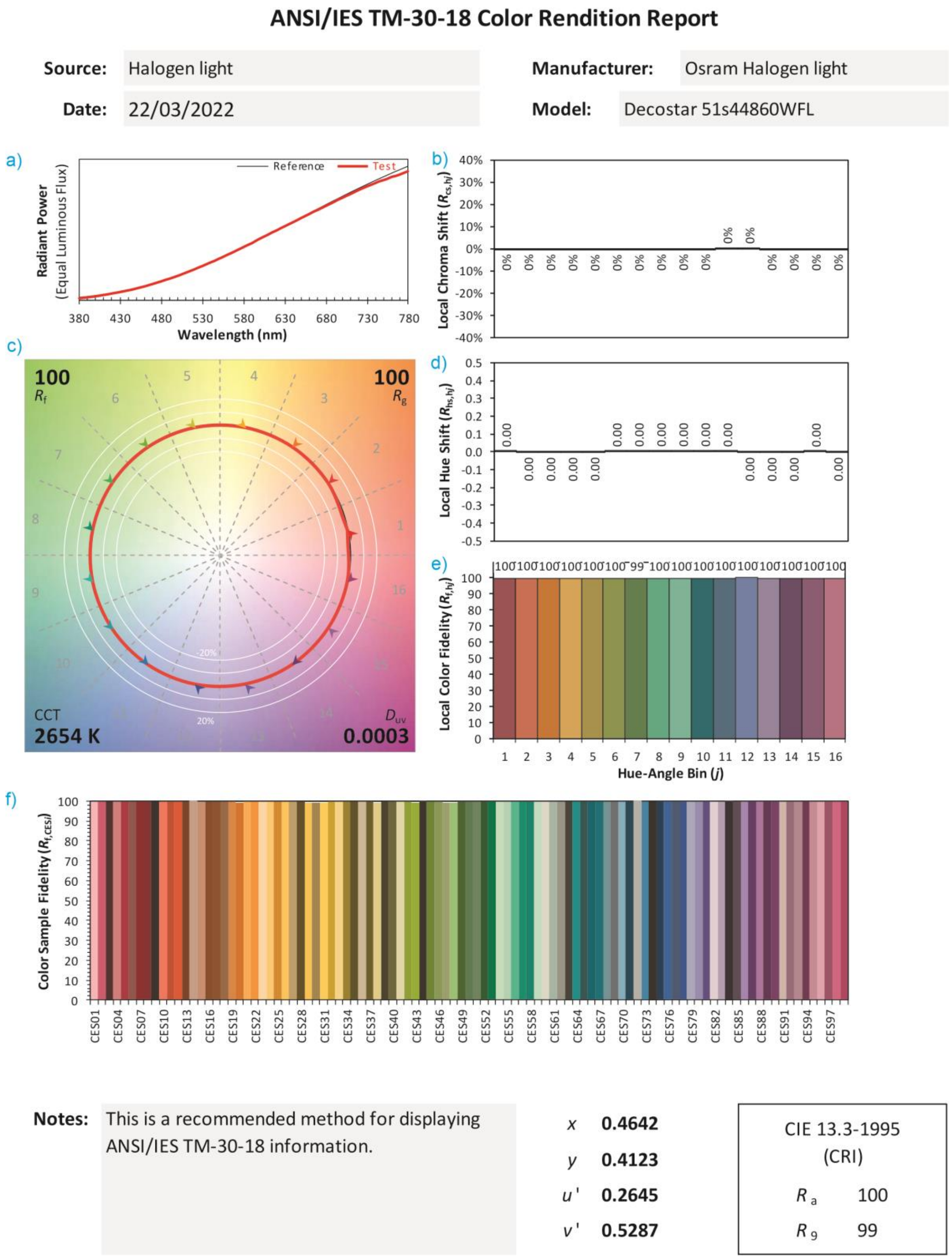


Figure 110. Measuring of Halogen Light a) Radiant power, b) Local chroma shift, c) TM-30-18 colour vector (CVGs) of, d) Local Hue shift, e) Local Color Fidelity, f) 99 Colour Samples

All the lighting used in this research has been set wavelength (nm) so that a comparative part can be seen together with their SPD of how close or opposite they are to each other.

At the (Figure 111) the LED lights have the same curves with the exception that according to CCT they differ from one another. While Wolfram Light and Halogen Light are in a common line.

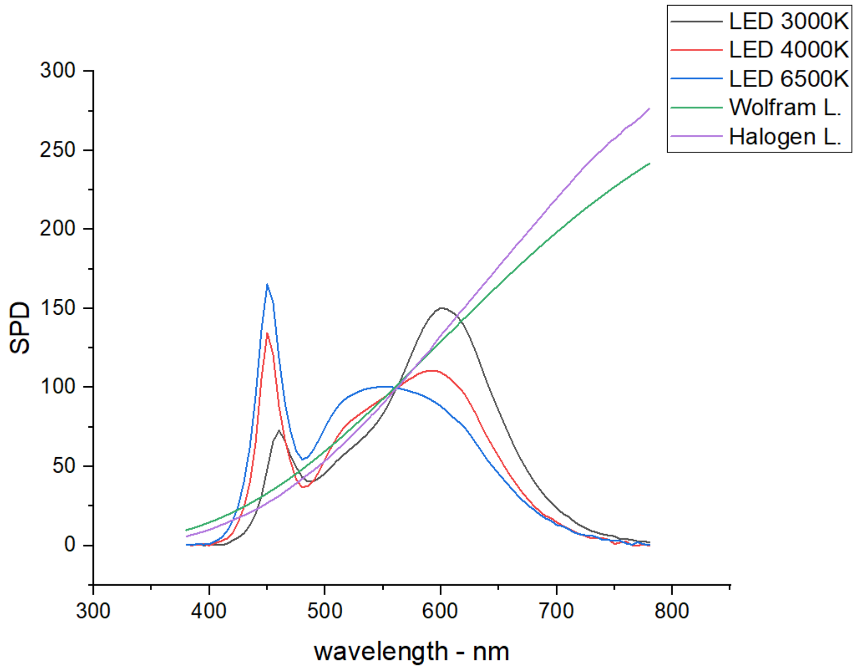


Figure 111. SPD of all light sources, to compare their wavelength (nm)

9. RESEARCH ON MUSEUM LIGHTING, GALLERIES, AND LIGHTING COMPANIES IN EU COUNTRIES

To obtain the most accurate results, field research was conducted in several museums, galleries, and lighting companies throughout Europe. Through close investigation and gathering precise information, the most suitable practises were identified, along with those that should be avoided due to their impact on the longevity of valuable artworks spanning hundreds or thousands of years. In addition, the enjoyable visitor experience plays an important role. High-quality lighting with a CRI (Colour Rendering Index) predominantly above 90 allows for a more realistic reproduction of the original colours.

Research initially began with museums and galleries in Zagreb. At the Modern Gallery on January 17, 2022, in Zagreb, Jura Jazbec, who was involved in exhibition preparations at the gallery, provided insights on how the lighting was selected by the curators. LED lights were primarily used, and lux levels were the basis. Graphics were illuminated up to 50 lux, while paintings were illuminated between 150-170 lux.

These details provided information on the lighting used and the space between the artworks and the lighting. Although the artist has a beautiful collection of works, it can be said that the quality of the lighting was not optimal for the preservation of the works. The lighting, based on information and visual observation, revealed instances of vertical or discontinuous lighting in a horizontal work of art. This caused the paintings to lack proper light or colour distribution, which impacts observers' subjective experience and the artworks objectively. The potential for damage to the artwork is present. In this gallery, older paintings are still illuminated with Halogen lights, as they are more suitable for the delicate nature and appropriate quality of older artworks.

At the Klovecivo Dvori Gallery in Zagreb, various exhibitions are held, and the gallery receives significant lights. There are different internal and external curators involved. In a conversation with the gallery's lighting technician, Mr. Tomislav Antolic, it was explained that they have different lighting setups for different areas of the gallery. The space differed from the Modern Gallery and natural lighting was also noticeable. Based on the gathered information, curators primarily determine the exhibition lighting based on the type of exhibition. The first floor was mainly illuminated with LED lights ranging from 3000K to 4000K for modern exhibitions, and

LED installations were used. However, there were also sections of older exhibitions still illuminated with halogen lights.
At Iluzija Gallery in Zagreb, which attracts many visitors due to its unique presentation of artworks and space, according to the gallery supervisor, the lighting was chosen by the architect who designed it, due to the lack of professional staff in this aspect. The lighting was predominantly LED at 4000K. Regarding the importance of CRI, there were no adequate individuals who paid attention to or prioritised it. Regarding lighting companies in Zagreb, so far, no lighting with a CRI above 90 has been found. Based on on-site research, the available and commonly used lighting in Croatia has a CRI value >80.
In the El Palace Gallery in Zadar, known as one of the galleries where the works of world-renowned artists are exhibited, the architectural aspect of the building, from the ground floor to the second floor, has a high ceiling distance and ample natural lighting through UV protectors from natural light. However, in the indoor exhibitions, there was insufficient visual lighting satisfaction due to various cuts in the lighting design on the artwork. After discussion with the lighting technicians, it was revealed that LED lighting was used mainly, depending on the different exhibitions and funding projects. The curators, in collaboration with the technicians, adjust the lighting as appropriately as possible.
At the National Gallery in Prishtina, Kosovo, during research on the lighting used in the museum, directors, curators, and lighting technicians were interviewed. As it was undergoing renovation, a more diverse lighting system was planned, meeting the minimum standards of European standards. LED lighting was used mainly, but when it comes to the quality and protection of the artworks, there was a lack of information and experts. Previously, Halogen lights were used in the National Gallery.
To have the opportunity for adequate lighting measurements and their spectrum through the Ceepus programme, I had the opportunity to conduct part of my research at Obuda University, Rejto Sandor Faculty of Light Industry and Environmental Engineering, in Budapest, Hungary. Here, under the mentorship of Prof. Ákos Borbély, I received consultations and conducted various measurements. However, with the help of Prof. Robert Hitchler on 23-24 March 2022, I had the opportunity to conduct more appropriate measurements at the University of Pannonia. With the assistance of Prof. Cecilia Lanyi and Róbert Nagy at this faculty, we had several colour and light research laboratories equipped with sophisticated devices such as Konica, Hunter Lab, etc. There, we conducted various tests and measurements using all the available apparatuses with my own artworks to see how they react to different lighting conditions produced by the university itself. During my research on lighting in museums and galleries, I came across

several different companies. Regarding the quality and importance of protecting artworks with specific characteristics, I found ERCO Lighting company. Initially, I researched various information about their LED lighting before visiting their headquarters in Vienna on March 14, 2022, which served as the main headquarters for several European countries. There, with the help of Markus Putzlager, I saw the nearby testing laboratory with homogeneous paintings and different high-quality lighting, suitable for the original colours of the paintings and providing a pleasant visual perception. With the visit to ERCO Lighting in Budapest on March 18, 2022, with the assistance of Mark Simon, I conducted tests on my own paintings for research in the testing laboratory to observe the reaction of illuminant metamerism effects on different painting techniques, starting from 2700K, 3000K, 3500K, 4000K CCT. Here, the lighting was adjusted with high-quality lighting filters and to optimize the distribution of light in different ways. These led lights are special because these are self-producers of LED lighting, with factory in Lüdenscheid, Germany. When visiting their factory in December 2022, I understood that only the initial material is obtained externally, while all other processes are carried out within the factory. There I had a meeting and assistance with Svenja Kallweit, who was responsible for staff training. The working meeting was fruitful and focused on lighting in museums, where we conducted tests in the lighting laboratory to analyse the qualitative differences that greatly affect specific technical aspects. Among other things, lux also influences the quality of a picture, although it may have a CRI higher than 90. Their lighting has a high cost but can be modified to achieve the same lighting effect with different CCTs (Correlated Colour Temperatures) and different cutting of radiation, which can be achieved through advanced technology and applications.

In March and April 2022, I visited famous museums in Vienna, Austria, with masterpieces by eminent artists such as in the Albertina Museum, Belvedere Palace, and Leopold Museum. Exposure lighting, with spotlights, was from LED lighting with CRI > 90. Depending on the period of the paintings, the lighting is also determined, as Renaissance and Baroque paintings require warmer lighting ranging from 2700K to 3500K, with 2W - 48W and 200lm - 6600lm, for the protection of the artworks and to provide a pleasant experience for visitors. Modern exhibitions or different installations are placed based on the choices of curators in collaboration with the artists and the adaptation of the exhibition to the venue where it will be held. In modern exhibitions, from the 19th century onwards to the present day, higher-temperature lighting is mainly used, ranging from 4000K to 5500K.

In Budapest, at the Museum of Fine Arts and the Hungarian National Museum, the qualitative LED lighting is the same as in the museums in Vienna; the difference lies only in the architecture of the specific building. However, in smaller galleries, there were still different older lighting setups. For example, at the Kiscell Museum in Budapest in March 2022, I had a very cooperative discussion with the internal staff and an interesting interior. They partially used qualitative LED spotlight lighting, while the rest of the lighting was arranged according to possibilities and costs.

On 29 June 2022, during a visit to the Vatican in the Sistine Chapel, I witnessed the new lighting project by Osram. The choice to modify the lighting scheme was made to effectively convey the significance and worth of the chapel's well-known artwork. Here, I saw excellent work and lighting similar to natural light, so the frescoes appeared lively due to the lighting and adaptation with the colours of the surrounding artworks. Moreover, it seemed to have an impact on the large number of visitors and a pleasant feeling, as it attracted visitors from all over the world. Other museums and galleries with similar lighting and qualitative specifics, based on personal visits, include the National Museum Ljubljana in Slovenia, the Goethe Museum in Dusseldorf, Germany, and various museums in Italy. The lighting, in addition to being from the same company, also had a variable lighting fluctuation ranging from 2700K to 4000K. It is important to have appropriate lighting in these environments to present the artworks perfectly, protect them, and provide a pleasant experience for visitors. Lighting technologies such as LED, ERCO lighting, and Osram Light offer various possibilities to adapt lighting to the specific needs of exhibitions.

In general, lighting in galleries, museums and exhibitions plays a critical role in presenting artwork and creating a suitable atmosphere for visitors. It is interesting to see how lighting technologies have evolved and how they are used to adapt lighting to the specific needs of each exhibition and location.

10. CONCLUSIONS

This doctoral thesis has centred its focus on the phenomenon of illuminant metamerism within the context of artistic paintings when subjected to various sources of illumination. The overarching objective has been to discern an optimal light source that mitigates perceptual irregularities and enhances average visual perception. A central hypothesis of this thesis posited that the presence of illuminant metamerism in paintings is contingent upon the specific painting techniques employed. The enquiry into illuminant metamerism has yielded compelling insights, unequivocally establishing that disparate painting techniques yield dissimilar appearances under diverse lighting conditions, substantiating the notion that individual observers perceive light in a distinctive manner. Furthermore, a noteworthy revelation lies in the effectiveness of standardised LED lighting in attenuating the manifestation of illuminant metamerism, particularly when characterised by a well-defined spectral power distribution. The import of future endeavours is directed towards the optimisation of lighting conditions to curtail variations in colour imagery. Within this framework, it becomes evident that the quantification of colour disparities is based on the foundation of the ΔE metric, thereby engendering the imperative use of the metamerism index (MI) to delineate the perceptual nuances of metamerism within the domain of art museum observation.

Artistic paintings, which are examples of a synthesis of diverse chemical compounds, are typified by pigments that selectively absorb and reflect specific wavelengths of light. The selection of subtractive colours from an original painting, predisposed to metamerism, engenders divergent spectral attributes that interact with distinct lighting scenarios. Thereby exerting a discernible impact upon the visual system, the comprehension of colour, and the manifestation of metamerism. Unique pigment characteristics, inherently affiliated with distinct painting techniques, impart a nuanced absorption profile, a phenomenon arising from the partial alignment of light absorption and reflexion with the human colour visual system, itself contingent upon the prevailing lighting environment. In essence, the conundrum of illuminant metamerism resides within the domain of colour perception, an intricate facet that can invariably attenuate the perceptual fidelity of the observer. Although the assessment of metamerism within monochromatic colour domains is relatively straightforward, the evaluation of halftone images under diverse luminous conditions necessitates the establishment of an objective metric capable of quantifying the gamut of colour distinctions.

This research has substantiated the feasibility of quantifying illuminant metamerism in halftone images through the adoption of a grey-balance field, meticulously reproduced via empirically tested samples. Within this framework, the divergences discernible within the grey balance field lend themselves amenable to quantification, thereby encapsulating the essence of metamerism via the metamerism index. In an endeavour to accentuate the vibrancy and intricacies intrinsic to tempera paintings, the prescription of a well-diffused, low-intensity light source is rendered judicious. A preference for warm white or neutral white lighting, typified by a correlated colour temperature (CCT) ranging from 3000K to 4000K, emerges as a tenable strategy.

Upon juxtaposing samples against the original tempera painting within diverse lighting contexts, it becomes distinctly clear that the preponderance of selected sample reproductions is pronounced within the realms of half-tones, specifically 2%C, 2%M, 4%D, and to some extent 6%D, -2%L, -4%L, -6%L. In stark contrast, the less favoured half-tones across all lighting instances constitute shades featuring elevated proportions, exemplified by 6%C, 6%M, as well as the cohort of yellow halftones, denoted as 2%Y, 4%Y, 6%Y. This discernment underpins the assertion that smaller half-tones, notably 2% and 4%, align harmoniously with the tempera colour technique, thereby minimizing the metamerism index contingent upon the predilection for specific hues.

In the realm of oil paintings, an efficacious strategy to counteract metamerism materialises in the form of a judiciously dispersed light source. Warm light or neutral white lighting, characterised by a CCT spanning 2700K to 4000K, stands as a prudent choice. The oil-colour technique, along with the metamerism index (MI), unveils a heightened propensity for variability vis-à-vis the tempera technique. Within this paradigm, sample reproductions most akin to the original painting, across all luminous contexts, converge at 4%C, 6%C, 2%M, and 2%D, while divergent expressions manifest within the purview of halftones, notably 4%M, 6%M, as well as the assemblage characterised by diminished half tones, i.e., -2%L, -4%L, -6%L. Notable is the discernment of disparate or heightened MI values within the purview of standard observers when navigating inter-luminous comparisons within the oil colour technique.

Regarding to acrylic paintings, a judicious amalgamation of warm and cool white-light sources, deftly diffused, serves as an effective measure to curb metamerism. Warm and cool white lighting, boasting a CCT range spanning 2700K, with particular emphasis on halogen light due to its inherently diminished MI values (such as 2%C, 2%M, 2%D), extending upwards to a CCT of 4000K, emerges as a befitting course of action. In the context of this technique, selected samples, juxtaposed against the pantheon of illuminations, invariably gravitate toward 2%M, 4%Y, and 2%D, all characterized by minimal MI values. On the contrary, the less favoured samples resonate with the higher proportional echelons, notably 6%C, 6%M, and 6%Y.

Watercolours find themselves exalted by a light source that adroitly straddles the realms of warmth and coldness, thereby accentuating their intrinsic delicacy contingent upon the pigments and suitable lighting for translucent colours. The ambit of suitable choices encompasses warm light or daylight lighting, encompassing a CCT spectrum spanning 2700K to 4000K. Exceptions arise in instances where the painting incorporates blue hues, wherein recourse to a cold light characterised by a CCT of 6500K is advisable. In the context of this technique, the prevailing tendencies gravitate towards the selection of halftones heralding modest MI values across disparate illuminations, typified by 2% C, 4% C, 2% M, 2% Y, and, to a limited extent, 2%D. In contrast, less favoured selections coalesce around halftones of maximal proportion, such as 6%C, 6%M, and -6%L.

In the context of pastel artworks, the orchestration of a well-diffused, low-intensity light source takes precedence in heightening the vivacity of colours and texture. A judicious alignment with warm white or neutral white lighting, typified by a CCT straddling the expanse of 2700K to 4000K, emerges as an eminently prudent selection. The technique of pastel colours unfurls an intricate mosaic of halftone choices, often diverging from the predilections heralded by the metamerism index (MI). Among the sample reproductions that invariably mirror the original painting, across the pantheon of illuminations, 2%Y and 4%Y. Concomitant to these favoured selections are halftones, specifically 6%Y, alongside the consortium that includes 2%D, 4%D, and 6%D. On the opposite end of the spectrum, diminished favour encompasses 2%C, the assemblage that encapsulates 2%M, 4%M, and 6%M, in addition to halftone ensembles marked by diminished values, embodied by -2%L, -4%L, and -6%L.

The quintessential confluence of warm white or neutral white lighting, within a CCT continuum of 2700K to 4000K, bequeaths the metamerism index with its most subdued manifestations.

10.1 Recommendations

An essential principle emphasized in this discussion concerns the fundamental significance of a robust Color Rendering Index (CRI) in accurately portraying the chromatic subtleties intrinsic to works of art. A threshold CRI of 90 or higher is conventionally upheld as a requisite prerequisite to underpin the veritable actualisation of faithful colour reproduction. A judicious manipulation of the light angle to an inclination of 30°, in tandem with the adroit diffusion of luminance, coalesce in an orchestration that foregrounds texture and brushwork, whilst judiciously obfuscating the advent of undue shadows. The luminance metric, quantified in lux, delineates the recommended range for museum illumination, which spans the range of 50 to 400 lux. Evidently, the precise quantum of illumination is contingent upon the specific exigencies underpinning the artwork in question.

It remains significant to acknowledge that the enunciated lighting recommendations constitute a confluence of insights gleaned from this research, alongside the broader fabric of research that spans the domains of museums, galleries, and lighting industries. The materialisation of precise lighting choices is inherently contingent upon a confluence of factors, ranging from the artist's intent through the prism of the discerning standard observers to the intricate tapestry of hues that bespeaks the painting's essence. Moreover, the manifold attributes of the artwork, along with the dynamics of printing reproduction, coalesce in shaping the choice of illumination. In a bid to dispel ambiguity and enshrine precision, the measured deployment of the metamerism index (MI) assumes an unequivocal imperative.

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12. APPENDIX

12.1 Appendix 1. - List of figures

12.2 Appendix 2. - List of tables

12.3 Appendix 3. - List of formulas

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12.4 Appendix 4. – Stastistical data processing

Appendix 4.1 - Subjective evaluation of all samples used for comparing Tempera colour painting under different light sources

Tempera c. Samples	LED 3000K	LED 4000 K	LED 6500 K	Wolfram L.	Halogen light
2%C	92	15	9	15	54
4%C	21	65	50	31	33
6%C	10	29	13	15	10
2%M	27	130	76	105	98
4%M	15	18	96	92	35
6%M	0	0	12	10	0
2%Y	23	15	15	14	35
4%Y	15	12	19	11	12
6%Y	5	15	15	8	8
2%D	15	14	5	12	27
4%D	62	102	12	85	74
6%D	15	18	84	56	23
-2%L	110	23	20	22	105
-4%L	31	85	21	35	29
-6%L	85	16	115	25	24

Appendix 4.2 Subjective evaluation of all samples used for comparing Oil colour painting under different light sources

Oil c. Samples	LED 3000K	LED 4000 K	LED 6500 K	Wolfram L.	Halogen light
2%C	15	85	19	15	25
4%C	115	92	20	88	62
6%C	73	20	13	120	95
2%M	90	18	22	24	105
4%M	18	11	5	11	19
6%M	19	32	12	10	21
2%Y	23	18	96	14	12
4%Y	17	72	60	21	15
6%Y	10	25	125	37	13
2%D	88	24	81	62	89
4%D	30	105	22	30	29
6%D	25	25	36	96	20
-2%L	16	18	20	13	22
-4%L	12	20	18	15	18
-6%L	8	13	16	10	20

Appendix 4.3 Subjective evaluation of all samples used for comparing Acryl colour painting under different light sources

Acryl c. Samples	LED 3000K	LED 4000 K	LED 6500 K	Wolfram Light	Halogen light
2%C	26	55	9	5	66
4%C	20	85	22	27	20
6%C	24	20	3	2	15
2%M	90	8	36	74	105
4%M	18	6	10	61	55
6%M	9	0	12	30	15
2%Y	23	49	5	14	30
4%Y	77	62	68	11	18
6%Y	5	25	15	7	9
2%D	17	14	55	12	92
4%D	69	13	12	24	25
6%D	45	7	6	57	20
-2%L	6	33	46	3	10
-4%L	8	6	100	0	3
-6%L	4	6	12	90	0

Appendix 4.4 Subjective evaluation of all samples used for comparing Pastel colour painting under different light sources

Pastel c. Samples	LED 3000K	LED 4000 K	LED 6500 K	Wolfram L.	Halogen light
2%C	6	25	9	5	15
4%C	9	75	22	27	5
6%C	37	30	78	62	3
2%M	30	8	26	14	22
4%M	18	6	30	11	24
6%M	9	0	12	10	18
2%Y	68	64	65	44	81
4%Y	76	48	19	110	56
6%Y	5	25	90	78	25
2%D	57	52	5	32	92
4%D	26	13	48	54	105
6%D	85	95	56	7	28
-2%L	6	3	6	3	15
-4%L	7	6	1	0	21
-6%L	4	6	12	0	6

Appendix 4.5 Subjective evaluation of all samples used for comparing Water colour painting under different light sources

Water c. Samples	LED light 3000K	LED light 4000 K	LED light 6500 K	Wolfiram L.	Halogen light
2%C	86	55	9	66	25
4%C	9	75	105	78	18
6%C	24	20	3	2	10
2%M	30	42	26	100	110
4%M	18	6	65	11	79
6%M	9	0	12	10	10
2%Y	52	90	86	14	65
4%Y	100	62	19	21	23
6%Y	5	25	15	47	9
2%D	37	14	75	32	92
4%D	26	13	12	24	26
6%D	15	7	46	85	22
-2%L	76	3	6	3	15
-4%L	47	6	1	0	30
-6%L	4	6	12	0	8

Appendix 4.6 L*a*b* values of five best matching of Tempera colour under different light sources

Tempero colour samples	Sample	L*	a*	b*
Tempero c. 1 LED L. 3000K	2%L	57.93	-6.183	-14.586
Tempero c. 2 LED L. 3000K	2%C	59.77	-6.271	-14.786
Tempero c. 3 LED L.3000K	6%L	63.29	-5.35	-15.456
Tempero c. 4 LED L.3000K	4%D	59.24	-5.226	-15.305
Tempero c. 5 LED L.3000K	4%L	59.94	-5.721	-16.184
Tempero c. 1 LED L. 4000K	2%M	47.417	-10.2	-18.28
Tempero c. 2 LED L. 4000K	4%D	59.23	-5.187	-15.313
Tempero c. 3 LED L. 4000K	4%L	59.958	-5.846	-16.351
Tempero c. 4 LED L. 4000K	4%C	53.449	-11.837	-19.669
Tempero c. 5 LED L. 4000K	6%C	58.412	-8.235	-16.268
Tempero c. 1 LED L. 6500K	6%L	63.238	-5.215	-15.284
Tempero c. 2 LED L. 6500K	4%M	49.346	-5.205	-19.824
Tempero c. 3 LED L. 6500K	6%D	53.629	-7.082	-10.852
Tempero c. 4 LED L. 6500K	2%M	53.764	-10.56	-20.636
Tempero c. 5 LED L. 6500K	4%C	53.437	-12.09	-19.199
Tempero c. 1 Wolfram L.	2%M	54.14	-10.45	-21.64
Tempero c. 2 Wolfram L.	4%M	49.13	-5.39	-19.67
Tempero c. 3 Wolfram L.	4%D	58.98	-5.45	-15.59
Tempero c. 4 Wolfram L.	6%D	53.629	-7.082	-10.852
Tempero c. 5 Wolfram L.	4%C	53.437	-12.088	-19.199
Tempero c. 1 Halogen L.	2%L	57.93	-6.18	-14.59
Tempero c. 2 Halogen L.	2%M	47.42	-10.20	-18.28
Tempero c. 3 Halogen L.	4%D	59.24	-5.23	-15.31
Tempero c. 4 Halogen L.	2%C	59.77	-6.27	-14.79
Tempero c. 5 Halogen L.	4%M	49.35	-5.21	-19.82

Appendix 4.7 L*a*b* values of five best matching of Oil colour under different light sources

Oil colour samples	Samples	L*	a*	b*
Oil c. 1 LED L. 3000K	4%C	56.665	-5.853	-16.736
Oil c. 2 LED L. 3000K	2%M	49.343	-5.696	-18.654
Oil c. 3 LED L. 3000K	2%D	44.511	-5.544	-15.869
Oil c. 4 LED L. 3000K	6%C	51.551	-8.788	-17.821
Oil c. 5 LED L. 3000K	4%D	43.644	-5.262	-10.471
Oil c. 1 LED L. 4000K	4%D	43.64	-5.26	-10.47
Oil c. 2 LED L. 4000K	4%C	56.67	-5.85	-16.74
Oil c. 3 LED L. 4000K	2%C	55.53	-5.92	-18.81
Oil c. 4 LED L. 4000K	4%Y	56.82	-3.73	-17.02
Oil c. 5 LED L. 4000K	6%M	45.44	-5.34	-13.65
Oil c. 1 LED. 6500K	6%Y	57.74	-3.34	-14.37
Oil c. 2 LED. 6500K	2%Y	59.31	-2.61	-15.48
Oil c. 3 LED. 6500K	2%D	44.51	-5.54	-15.87
Oil c. 4 LED. 6500K	4%Y	56.82	-3.73	-17.02
Oil c. 5 LED. 6500K	6%D	43.23	-3.89	-10.21
Oil c. 1 Wolfram L.	6%C	51.551	-8.788	-17.821
Oil c. 2 Wolfram L.	6%D	43.227	-3.89	-10.21
Oil c. 3 Wolfram L.	4%C	56.665	-5.853	-16.736
Oil c. 4 Wolfram L.	2%D	44.511	-5.544	-15.869
Oil c. 5 Wolfram L.	6%Y	57.741	-3.335	-14.37
Oil c. 1 Halogen L.	2%M	49.34	-5.70	-18.65
Oil c. 2 Halogen L.	6%C	51.55	-8.79	-17.82
Oil c. 3 Halogen L.	2%D	44.51	-5.54	-15.87
Oil c. 4 Halogen L.	4%C	56.67	-5.85	-16.74
Oil c. 5 Halogen L.	4%D	43.64	-5.26	-10.47

Appendix 4.8 L*a*b* values of five best matching of Acryl colour under different light sources

Acryl colour samples	Samples	L*	a*	b*
Acryl c. 1 LED L. 3000K	2%M	53.65	-10.54	-20.50
Acryl c. 2 LED L. 3000K	4%Y	51.11	-7.46	-8.13
Acryl c. 3 LED L. 3000K	4%D	58.24	-6.33	-15.10
Acryl c. 4 LED L. 3000K	6%D	51.93	-8.68	-9.65
Acryl c. 5 LED L. 3000K	2%C	58.54	-7.20	-15.63
Acryl c. 1 LED L. 4000K	4%C	53.46	-11.77	-19.47
Acryl c. 2 LED L. 4000K	4%Y	51.11	-7.46	-8.13
Acryl c. 3 LED L. 4000K	2%C	58.54	-7.20	-15.63
Acryl c. 4 LED L. 4000K	2%Y	52.20	-7.359	-14.313
Acryl c. 5 LED L. 4000K	-2%L	53.21	-7.822	-13.43
Acryl c. 1 LED L. 6500K	2%M	53.65	-10.54	-20.50
Acryl c. 2 LED L. 6500K	-2%L	53.21	-7.82	-13.43
Acryl c. 3 LED L. 6500K	-4%L	52.48	-8.10	-12.00
Acryl c. 4 LED L. 6500K	4%Y	51.11	-7.46	-8.13
Acryl c. 5 LED L. 6500K	2%D	55.71	-6.73	-14.46
Acryl c. 1 Wolfram L.	6%L	57.62	-6.66	-10.60
Acryl c. 2 Wolfram L.	2%M	53.65	-10.54	-20.50
Acryl c. 3 Wolfram L.	4%M	51.75	-8.96	-19.21
Acryl c. 4 Wolfram L.	6%D	51.93	-8.68	-9.65
Acryl c. 5 Wolfram L.	6%M	51.624	-7.601	-15.476
Acryl c. 1 Halogen L.	2%M	53.65	-10.54	-20.50
Acryl c. 2 Halogen L.	2%D	55.71	-6.73	-14.46
Acryl c. 3 Halogen L.	2%C	58.54	-7.20	-15.63
Acryl c. 4 Halogen L.	4%M	51.75	-8.96	-19.21
Acryl c. 5 Halogen L.	2%Y	52.20	-7.36	-14.31

Appendix 4.9 L*a*b* values of five best matching of Pastel colour under different light sources

Pastel colour samples	**Samples**	**L***	**a***	**b***
Pastel c. 1 LED L. 3000K	6%D	54.277	-5.348	-12.171
Pastel c. 2 LED L. 3000K	4%Y	58.428	-4.538	-7.42
Pastel c. 3 LED L. 3000K	2%Y	59.505	-3.395	-11.545
Pastel c. 4 LED L. 3000K	2%D	57.296	-4.434	-15.3
Pastel c. 5 LED L. 3000K	6%C	55.383	-8.006	-17.805
Pastel c. 1 LED L. 4000K	6%D	54.28	-5.35	-12.17
Pastel c. 2 LED L. 4000K	4%C	59.46	-4.54	-19.75
Pastel c. 3 LED L. 4000K	2%Y	59.51	-3.40	-11.55
Pastel c. 4 LED L. 4000K	2%D	57.30	-4.43	-15.30
Pastel c. 5 LED L. 4000K	4%Y	58.43	-4.54	-7.42
Pastel c. 1 LED L. 6500K	6%Y	59.02	-4.31	-8.61
Pastel c. 2 LED L. 6500K	6%C	55.38	-8.01	-17.81
Pastel c. 3 LED L. 6500K	2%Y	59.51	-3.395	-11.55
Pastel c. 4 LED L. 6500K	6%D	54.28	-5.348	-12.17
Pastel c. 5 LED L. 6500K	4%D	59.32	-2.75	-16.58
Pastel c. 1 Wolfram L.	4%Y	58.43	-4.54	-7.42
Pastel c. 2 Wolfram L.	6%Y	59.02	-4.31	-8.61
Pastel c. 3 Wolfram L.	6%C	55.38	-8.01	-17.81
Pastel c. 4 Wolfram L.	4%D	59.28	-2.78	-16.57
Pastel c. 5 Wolfram L.	2%Y	59.51	-3.40	-11.55
Pastel c. 1 Halogen L.	4%D	59.32	-2.75	-16.58
Pastel c. 2 Halogen L.	2%D	57.30	-4.43	-15.30
Pastel c. 3 Halogen L.	2%Y	59.51	-3.40	-11.55
Pastel c. 4 Halogen L.	4%Y	58.43	-4.54	-7.42
Pastel c. 5 Halogen L.	6%D	54.28	-5.35	-12.17

Appendix 4.10 L*a*b* values of five best matching of Water colour under different light sources.

Water colour samples	Samples	L*	a*	b*
Water c. 1 LED L. 3000K	4%Y	60.62	-2.56	-15.48
Water c. 2 LED L. 3000K	2%C	53.58	-7.42	-17.36
Water c. 3 LED L. 3000K	-2%L	63.97	-4.52	-17.39
Water c. 4 LED L. 3000K	2%Y	58.49	-4.50	-10.63
Water c. 5 LED L. 3000K	-4%L	61.74	-2.39	-17.62
Water c. 1 LED L. 4000K	2%Y	58.49	-4.50	-10.63
Water c. 2 LED L. 4000K	4%C	54.60	-6.04	-16.72
Water c. 3 LED L. 4000K	4%Y	60.67	-2.56	-15.48
Water c. 4 LED L. 4000K	2%C	53.58	-7.42	-17.50
Water c. 5 LED L. 4000K	2%M	58.38	0.28	-15.39
Water c. 1 LED L. 6500K	4%C	54.60	-6.04	-16.72
Water c. 2 LED L. 6500K	2%Y	58.49	-4.50	-10.63
Water c. 3 LED L. 6500K	2%D	57.27	-4.3	-16.42
Water c. 4 LED L. 6500K	4%M	59.92	-1.81	-18.09
Water c. 5 LED L. 6500K	6%D	53.79	-5.33	-11.66
Water c. 1 Wolfram L.	2%M	58.38	0.28	-15.39
Water c. 2 Wolfram L.	6%D	53.79	-5.33	-11.66
Water c. 3 Wolfram L.	4%C	54.60	-6.04	-16.72
Water c. 4 Wolfram L.	2%C	53.58	-7.42	-17.50
Water c. 5 Wolfram L.	6%Y	58.15	-4.03	-7.39
Water c. 1 Halogen L.	2%M	58.38	0.275	-15.39
Water c. 2 Halogen L.	2%D	57.27	-4.3	-16.42
Water c. 3 Halogen L.	4%M	59.92	-1.81	-18.09
Water c. 4 Halogen L.	2%Y	58.49	-4.50	-10.63
Water c. 5 Halogen L.	4%L	61.74	-2.39	-17.62

Appendix 4.11 SPD of different light sources with their wavelengths - nm

Nm	LED Light 3000K	LED Light 4000K	LED Light 6500K	Wolfram Light I.A	Halogen Light
380	0.691699536	0.449644975	0.413451038	9.7951	5.793991416
385	0.308383713	0.211646355	0.418810492	10.8996	6.909871245
390	1.1597967	0.648156711	1.02384502	12.0853	7.811158798
395	0.179538004	0.810981914	0.758997415	13.3543	8.841201717
400	0.372269879	0.095665102	1.083273707	14.708	10.08583691
405	0.379631674	1.670449785	2.725907727	16.148	11.41630901
410	0.441099203	2.744657867	4.905864014	17.6753	13.00429185
415	1.070364755	4.472792869	8.85594067	19.2907	14.3776824
420	3.27909017	8.12270398	15.67750769	20.995	16.13733906
425	5.228237893	15.30749671	25.49408701	22.7883	17.68240343
430	7.806349978	24.77426679	41.01748937	24.6709	19.22746781
435	13.05618857	40.1631093	62.93662168	26.6425	21.03004292
440	19.9362834	65.48087982	94.79744527	28.7027	22.83261803
445	31.34021526	105.7064288	136.6138341	30.8508	24.63519313
450	48.34349798	134.5816832	165.3608138	33.0859	26.9527897
455	65.84845392	121.1039992	153.8244938	35.4068	29.1416309
460	72.82776573	88.42738235	119.0765753	37.8121	31.37339056
465	66.5618974	67.72447085	91.2557471	40.3002	34.03433476
470	56.79579902	53.20079447	72.51294443	42.8693	36.60944206
475	49.52272306	41.8176076	59.81292126	45.5174	39.39914163
480	43.6385767	36.81825265	54.59013104	48.2423	42.06008584
485	40.47962153	37.68657313	55.86791124	51.0418	45.06437768
490	40.67603812	41.00023459	60.66591853	53.9132	47.63948498
495	42.84697062	47.33815074	67.74113172	56.8539	50.64377682
500	45.92010201	54.55859237	74.99694632	59.8611	53.64806867
505	49.74290569	61.94596121	81.76181372	62.932	57.08154506
510	53.54260487	68.33142002	87.32701161	66.0635	60.51502146
515	56.890664	73.65356948	91.43688511	69.2525	63.94849785
520	60.05548064	77.59862346	94.20207984	72.4959	67.38197425
525	63.00917009	80.56121142	95.9600964	75.7903	71.24463519
530	66.2084514	83.2132038	97.72911328	79.1326	74.67811159

535	**69.6569311**	**85.84125916**	**99.07852966**	**82.5193**	**78.54077253**
540	73.57457841	88.52160451	99.75352381	85.947	82.40343348
545	78.12992518	90.7477861	100.2513268	89.4124	85.83690987
550	83.52607464	93.33178994	100.4053523	92.912	90.12875536
555	89.79029976	95.902939	100.3189032	96.4423	93.99141631
560	97.00269088	98.73465942	100.2033434	100	98.2832618
565	104.5456298	101.3624142	99.22034756	103.582	102.1459227
570	112.9286601	104.0384978	98.39850136	107.184	106.4377682
575	121.8951711	106.17858	97.20397898	110.803	110.7296137
580	130.2419014	108.4079291	96.07174463	114.436	115.0214592
585	138.0020566	110.0304908	94.69302703	118.08	119.3133047
590	143.898808	110.776939	92.67504159	121.731	123.1759657
595	148.1467399	110.7706041	90.68761414	125.386	128.3261803
600	150.3855561	109.5534535	88.18359564	129.043	133.0472103
605	149.6842837	107.2697491	85.06713227	132.697	137.3390558
610	147.5987482	104.2352345	81.47243066	136.346	141.6309013
615	144.2796764	100.4332786	78.44461936	139.988	146.3519313
620	139.0775036	96.43633538	75.1986446	143.618	150.2145923
625	131.4893587	90.00886733	70.32439766	147.235	154.9356223
630	122.6413791	83.38548717	64.85715056	150.836	159.2274678
635	112.9362145	75.83216217	59.85712726	154.418	163.5193133
640	102.7642156	68.70719119	54.18330305	157.979	167.8111588
645	93.85971963	62.31472699	49.72544406	161.516	172.1030043
650	85.06981425	56.17012579	45.35002387	165.028	176.8240343
655	76.542886	49.82948147	41.10518826	168.51	181.1158798
660	68.0554943	44.05435507	36.8571966	171.963	185.4077253
665	60.11612281	38.90157275	32.76600387	175.383	190.1287554
670	53.13947854	33.85379813	29.09650437	178.769	193.9914163
675	47.02023264	29.57713624	25.55938919	182.118	198.2832618
680	41.12883056	25.4234564	22.99248674	185.429	202.5751073
685	35.93532266	21.9241443	19.87809493	188.701	206.8669528
690	31.29750042	18.90811343	17.37508326	191.931	211.1587983
695	27.62177231	17.35101863	15.7805449	195.118	215.8798283

700	**23.80998381**	**14.80180439**	**13.07576575**	**198.261**	**219.7424893**
705	20.47350112	12.52336673	12.28789413	201.359	224.0343348
710	18.34443411	10.72770088	10.4161253	204.409	227.8969957
715	15.23482068	8.907546219	8.419169661	207.411	232.1888412
720	12.90874596	7.169541164	7.192343924	210.365	236.4806867
725	10.94746532	6.04110016	6.415308114	213.268	240.3433476
730	9.299340099	4.564065675	6.433295531	216.12	244.2060086
735	8.174858706	4.686499689	5.23959429	218.92	247.639485
740	7.135541671	4.625941875	3.475641933	221.667	251.0729614
745	6.467342577	3.716264289	3.508019002	224.361	254.9356223
750	5.8941806	1.043821489	3.075763156	227	257.5107296
755	4.096329346	1.959602923	3.062609712	229.585	260.5150215
760	4.195958835	2.470375893	1.360222037	232.115	264.3776824
765	3.63322169	0.255382285	0.606111217	234.589	266.5236052
770	2.75793797	0	2.229990304	237.008	269.527897
775	2.7206233	0.754255565	0.839868352	239.37	272.9613734
780	2.078281669	0	0.665374518	241.675	276.3948498

Appendix 4.12 Measuring wavelength of light (nm) of XYZ colour matching functions

l, nm	x_(λ)	y_(λ)	z_(λ)	*x*(*l*)	*y*(*l*)
380	0.001368	0.000039	0.006450	0.174110	0.004960
385	0.002236	0.000064	0.010550	0.174010	0.004980
390	0.004243	0.000120	0.020050	0.173800	0.004920
395	0.007650	0.000217	0.036210	0.173560	0.004920
400	0.014310	0.000396	0.067850	0.173340	0.004800
405	0.023190	0.000640	0.110200	0.173020	0.004780
410	0.043510	0.001210	0.207400	0.172580	0.004800
415	0.077630	0.002180	0.371300	0.172090	0.004830
420	0.134380	0.004000	0.645600	0.171410	0.005100
425	0.214770	0.007300	1.039050	0.170300	0.005790
430	0.283900	0.011600	1.385600	0.168880	0.006900
435	0.328500	0.016840	1.622960	0.166900	0.008560
440	0.348280	0.023000	1.747060	0.164410	0.010860
445	0.348060	0.029800	1.782600	0.161100	0.013790
450	0.336200	0.038000	1.772110	0.156640	0.017700
455	0.318700	0.048000	1.744100	0.150990	0.022740
460	0.290800	0.060000	1.669200	0.143960	0.029700
465	0.251100	0.073900	1.528100	0.135500	0.039880
470	0.195360	0.090980	1.287640	0.124120	0.057800
475	0.142100	0.112600	1.041900	0.109590	0.086840
480	0.095640	0.139020	0.812950	0.091290	0.132700
485	0.057950	0.169300	0.616200	0.068710	0.200720
490	0.032010	0.208020	0.465180	0.045390	0.294980
495	0.014700	0.258600	0.353300	0.023460	0.412700
500	0.004900	0.323000	0.272000	0.008170	0.538420
505	0.002400	0.407300	0.212300	0.003860	0.654820
510	0.009300	0.503000	0.158200	0.013870	0.750190
515	0.029100	0.608200	0.111700	0.038850	0.812020
520	0.063270	0.710000	0.078250	0.074300	0.833800
525	0.109600	0.793200	0.057250	0.114160	0.826210
530	0.165500	0.862000	0.042160	0.154720	0.805860
535	0.225750	0.914850	0.029840	0.192880	0.781630

540	0.290400	0.954000	0.020300	0.229620	0.754330
545	0.359700	0.980300	0.013400	0.265780	0.724320
550	0.433450	0.994950	0.008750	0.301600	0.692310
555	0.512050	1.000000	0.005750	0.337360	0.658850
560	0.594500	0.995000	0.003900	0.373100	0.624450
565	0.678400	0.978600	0.002750	0.408740	0.589610
570	0.762100	0.952000	0.002100	0.444060	0.554710
575	0.842500	0.915400	0.001800	0.478770	0.520200
580	0.916300	0.870000	0.001650	0.512490	0.486590
585	0.978600	0.816300	0.001400	0.544790	0.454430
590	1.026300	0.757000	0.001100	0.575150	0.424230
595	1.056700	0.694900	0.001000	0.602930	0.396500
600	1.062200	0.631000	0.000800	0.627040	0.372490
605	1.045600	0.566800	0.000600	0.648230	0.351390
610	1.002600	0.503000	0.000340	0.665760	0.334010
615	0.938400	0.441200	0.000240	0.680080	0.319750
620	0.854450	0.381000	0.000190	0.691500	0.308340
625	0.751400	0.321000	0.000100	0.700610	0.299300
630	0.642400	0.265000	0.000050	0.707920	0.292030
635	0.541900	0.217000	0.000030	0.714030	0.285930
640	0.447900	0.175000	0.000020	0.719030	0.280930
645	0.360800	0.138200	0.000010	0.723030	0.276950
650	0.283500	0.107000	0.000000	0.725990	0.274010
655	0.218700	0.081600	0.000000	0.728270	0.271730
660	0.164900	0.061000	0.000000	0.729970	0.270030
665	0.121200	0.044580	0.000000	0.731090	0.268910
670	0.087400	0.032000	0.000000	0.731990	0.268010
675	0.063600	0.023200	0.000000	0.732720	0.267280
680	0.046770	0.017000	0.000000	0.733420	0.266580
685	0.032900	0.011920	0.000000	0.734050	0.265950
690	0.022700	0.008210	0.000000	0.734390	0.265610
695	0.015840	0.005723	0.000000	0.734590	0.265410
700	0.011359	0.004102	0.000000	0.734690	0.265310

705	0.008111	0.002929	0.000000	0.734690	0.265310
710	0.005790	0.002091	0.000000	0.734690	0.265310
715	0.004109	0.001484	0.000000	0.734690	0.265310
720	0.002899	0.001047	0.000000	0.734690	0.265310
725	0.002049	0.000740	0.000000	0.734690	0.265310
730	0.001440	0.000520	0.000000	0.734690	0.265310
735	0.001000	0.000361	0.000000	0.734690	0.265310
740	0.000690	0.000249	0.000000	0.734690	0.265310
745	0.000476	0.000172	0.000000	0.734690	0.265310
750	0.000332	0.000120	0.000000	0.734690	0.265310
755	0.000235	0.000085	0.000000	0.734690	0.265310
760	0.000166	0.000060	0.000000	0.734690	0.265310
765	0.000117	0.000042	0.000000	0.734690	0.265310
770	0.000083	0.000030	0.000000	0.734690	0.265310
775	0.000059	0.000021	0.000000	0.734690	0.265310
780	0.000042	0.000015	0.000000	0.734690	0.265310

13. BIBLIOGRAPHY

Albulena Bilalli was born in 1988 in Pristina, Kosovo. She successfully completed her undergraduate studies in 2009 and postgraduate studies in 2012 at the University of Prishtina, Faculty of Arts, specialising in Graphics. In 2012 she was elected a distinguished student for Graphic achievement

Currently, she pursued her undergraduate studies at the Faculty of Philology of the University of Prishtina, focusing on Comparative Literature and Albanian Literature from 2012 to 2016.
In 2014, she completed a training programme at the University of the Arts London – Central Saint Martins, specialising in experimental printmaking within the Graphic department. Her academic journey continued as she enroled in the postgraduate doctoral programme in Graphic Engineering and Graphic Product Design in 2016 at the Faculty of Graphic Arts in Zagreb.
During her pursuit of the doctoral degree, Albulena participated in international conferences and contributed to the field of colour science, metamerism, and colorimetry in graphic technology and artwork through the publication of numerous scientific papers.

Her scholarly achievements include being awarded the Ceepus network scholarship in 2022 for doctoral research at Obuda University, Rejto Sandor Faculty of Light Industry Engineering. In the same period, she collaborated with the University of Pannonia and LightingLab Veszprem, Hungary, and for research focused on colour and lighting measurements. In particular, she partnered with ERCO lighting company in Germany, Austria, and Hungary in 2022 for her doctoral research on qualitative lighting in museums, different environments, and the implications of illuminant metamerism on visual perception.

During her academic journey, Albulena gained practical experience as a UV machine press operator at the Lino design studio in Prishtina, Kosovo. Since 2011, she has been a professor of professional subjects in the Graphics field at the 28 Nentori technical high school in Prishtina, Kosovo.
Her involvement also extended to serving as a draftsman for projects at the Archaeological Institute of Kosovo in Ulpiane during 2013-2014. Since 2019, she has been an active member of the editorial board and an Albanian language lecturer for the "Informatori" magazine in Zagreb, Croatia. Between 2020 and 2022, Albulena collaborated on quality control and management research with the Flexograf printing company in Gjilan, Kosovo. In 2022, she

engaged in an exploration of colours and their application in ceramics at the Vilhart workshop in Zadar, Croatia.

Albulena's artistic journey is marked by five personal exhibitions on an international platform, predominantly showcasing graphic printmaking. Additionally, she has contributed to around 30 collective exhibitions, further establishing her presence and contributions in the artistic domain.

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