Exploring opportunities of complex LED colour mix systems for lighting in the art

Fine colour tuning a painting

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Exploring opportunities of complex LED colour mix systems for lighting in the art. Fine colour tuning a painting

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ABSTRACT

Museums and the performing arts have very specific lighting requirements, not only in the technical aspects of their presentation, but also in regard to the communication and interpretation of artistic concepts. Thus, the design intent might have many different perspectives whereas the idea of being “neutral” is more complex to define.

One of the critical aspects for the visual experience of art is colour, a subjective experience that can be conceptually approached from many perspectives, from science to the artistic realm. This study starts by setting a theoretical framework in colour human vision, colour theory and colourimetry; and how this can be applied to lighting design concepts for exhibitions.

The experimental part of this work explores some of the opportunities of complex LED colour mix systems in working with fine colour tuning and metamer.s. This investigation focusses on both the creation of the light stimuli and on how these lighting conditions can influence the perception and interpretation of a painting.

In spite of its subjectivity, the perception of the art is contextualized with the colour theory background provided, the quantitative measurements performed and the results of an online survey. Additionally, the artist is interviewed in an attempt to gather views from the origin of the artwork to the viewer interpretation.

This work might be useful to those with interest in the opportunities that quality LED technology, specifically colour mixing, offer for lighting design in exhibition and theatre environment. In fact, the complexity of exhibition lighting provides a perfect environment for research and experimentation, where improving the viewer experience is becoming an essential factor for museology.

Keywords

Art lighting, museum lighting, exhibition lighting, theatre lighting, lighting design, LED colour mixing, additive mixing, CIE colour space, metamer.s, white light, colour rendition, colour perception, ETC seven colour system.
1. INTRODUCTION

Light is necessary to make things visible, however light also influences the appearance of what we see. The nature of lighting is bound to the visual experience of art, where its presentation has become a high profile industry (Cuttle, 2007). In exhibitions, light interprets and communicates a conceptually based approach to art (Schielke, 2020); in theatres, light communicates and contributes to the storytelling (Taylor, 2019). These lighting design concepts are increasingly important in architectural environments.

LED technology is extending to all spheres of activity, with important environmental benefits over previous technologies (EERE, 2013). However, the imposed directives and wholesale adoption of LED, are often conflicting with the high demands of the performing arts and museums in terms of quality and cost (ALD, 2019).

One critical aspect for art display (as well as for LED technology) is colour reproduction, but metrics do not tell the whole story when it comes to human perception and light quality. The appearance of scenes, materials, pigments or people is affected by the quality and complexity of the light source.

LED colour mix sources are developing and allow a more complex manipulation of colour, demanding new ways of thinking and methodologies, and posing new challenges for the design intent (Taylor, 2019). One of the challenges is to think about the opportunities offered by such systems, rather than their limitations or comparisons with traditional light sources. Biologically, humans adapt and learn to see differently; in fact, current media and coloured light is slowly shifting our vision (Besenecker, 2016).

“Colour is a rather subjective experience” (Taylor, 2019); scientists, philosophers and artists would approach the subject in a different way (Lamb and Bourriaud, 1995). However, there are common physical, biological, physiological and psychological processes which have been explored in both science and art revealing important knowledge about the way we see (Livingstone, 2014).

The first part of this thesis covers technical and theoretical aspects of colour, from human vision to colorimetry, in an attempt to provide the reader with the theoretical knowledge needed to explore the opportunities of multiple colour LED fixtures in museum and theatre environments. Thus, the experimental procedure aims to investigate the possibilities of “complex” LED colour mix systems (other than white tuning or RGB) on creating metameric lighting conditions (virtually identical colour metrics but different spectra composition) and fine tuning of “white light”; and how these conditions might influence the perception and interpretation of an art piece, paintings in this particular study.

‘The painting must reveal itself in different aspects if the moods of light are included in its viewing, in its seeing.’ (Kahn and Kimbell Art Museum, 1975).

Exhibition lighting design is a process involving many different perspectives and considerations from preservation of the content to revealing the detail and emotional power of the artwork (Hurlbert and Cuttle, 2020). In this context, the concept of a “suitable” lighting concept, being “neutral” or respecting the original intentions of the artists arouses many questions (Schielke, 2020), especially in an environment where the focus is shifting towards the visitor experience (Iannone, 2017; Maccheroni, 2018).

At the time of this writing, the world is immersed in a pandemic situation with COVID-19, which will affect how art is delivered to the audience in the, at least, near future. Museum executives foretell smaller crowds visiting exhibitions simultaneously in a “less touristic” experience, where a successful visit will be likely to be measured qualitatively rather than quantitatively (Riaño, 2020).
2. BACKGROUND

2.1. Colour vision: trichromacy & colour opponents

We all see colours differently. The perception and representation of a certain colour in our brain will be distinct for each of us, even if we agree on the physics or how we describe it. Besides shared physiological, biological and psychological processes, visual experience is individual and depends on memories, contexts or conditions.

Having said this, light is energy, electromagnetic radiation, and atoms within a molecule of matter (for example a pigment) will absorb or reflect photons depending on the wavelength. “...for us to see that an object has a colour, it is because the colour is present in the light that is reflected from the object into our eyes” (Taylor, 2019, p. 13).

Reflected photons are focused by the cornea (lens) into the eye, hitting certain photoreceptor cells on the retina. This causes an electro-chemical reaction, which in turn causes the brain to perceive a colour at that location. Currently, It seems to be accepted that “colour vision has two faces: It is both trichromatic and colour opponent” (Livingstone, 2014, p. 64).

At the photoreceptor level, humans are trichromatic since we usually have three different kinds of cell: S-cones, M-cones and L-cones. Each cone type contains a pigment which makes them more sensitive to a different range of wavelengths in the visible spectrum: Short (blue), Middle (green) and Long (red) respectively.

Another set of photoreceptors, the rods, outnumber the cones; being responsible for our significant sensitivity to light levels. Rods kick in at low light levels and their response is limited to a particular set of wavelengths, although they don’t seem to contribute to the sensation of colour. More recently, a fifth set of photoreceptors was discovered, the ipRGCs, but it is still uncertain if they affect colour vision (Zele et al., 2018).

Figure 1. Illustration of distribution of cone cells in the central part of the retina (fovea) for an average [left] vs. a colour-blind [right] person. The physical configuration of the cells on the back of the retina is unique between individuals, “like a fingerprint” (Taylor, 2019); Humans have very few blue-sensitivity cones at the centre of the fovea. Image: CC BY-SA 3.0 (Fairchild, 2010)

Figure 2. Normalized spectral absorption curves of S, M, L cones and rod (R) cells. Photoreceptor responses increase with the amount of light, but the relationship between the magnitude of the response and the number of photons varies with the wavelength. Created in Excel and Vectorworks using data from Stockman & Sharpe (2000) (CVRL, no date) and colour band image on CC BY-SA 3.0 (User: Army1987, 2008)
At a neurological level, human colour vision turns into colour opponency where the appearance of an object, or light source, is determined by neural mechanisms that process signals from the cones. According to this theory, the human visual system creates three channels: two spectrally opponent, blue versus yellow and red vs green and one achromatic, or luminance channel (Rea and Freyssinier, 2013).

As a visual stimulus, light can be specified in terms of three numbers that are related to the bioelectrical signals elicited in the retina (Schanda, 2007). This concept can be related to how colour is expressed in certain colour systems (i.e. CIE colour space).

In a later process, the brain analyses these signals and creates a picture of reality including the experience of colour. “Colour as we know it, only exists in our brain” (Taylor, 2019, p. 15)

2.2. Colour theory: colour, luminance and contrast

“It is impossible to have light without colour. All visible light is colour” (Taylor, 2019, p. 19).

2.2.1. Primary and complementary colours

In lighting, we consider red, green and blue as the primary colours, these cannot be generated from any other colour mix and follow our trichromatic nature. Thus, all the colours we see, including white, are generated from responses to these wavelength ranges. Biologically, colour opponency accounts for complementary colours. Red, green, yellow, and blue are so-called unique hues because these colour sensations are created by signals from just one of the two spectrally opponent channels (Rea and Freyssinier, 2013).

The concept of complementary colours was introduced by Goethe in his book *Theory of colours* at the beginning of the 19th century in a conceptually different approach to Newton’s theory of colour. Newton had arranged the colours, that he discovered to form the visible spectrum, in what seems to be the first ever colour circle. In this circle, both ends of the spectrum were joint with a mix of red and blue: what we mostly know as magenta.
There are several versions of the colour circle (or colour wheel) depending on what colours, saturations, shades, or other distinctions, are included. The colours to be considered primary will vary depending on whether you are an artist, print images, one interested in after images or work with light. Colour mixing for paints works subtractive, but in lighting, colour mixing is additive.

For lighting, secondary colours comprise a wider range of frequencies and remain saturated; “at the same level of saturation cyan can render more local pigment colours (in costumes and scenery) than blue or green” (Taylor, 2019, p. 73).

2.2.2. Luminance, adding the third dimension

“Luminance, or what artists refer to as value, is perceived lightness. It is defined by how the human visual system responds to light, how bright the average human judges a light to be” (Livingstone, 2014, p. 31). Lightness, as a perceptual measure, is dependent on the different sensitivity on the human eye to different wavelengths. “The achromatic channel is mainly responsible for our sensation of lightness or luminance” (Rea and Freyssinier, 2013),

Although colour and luminance seem to be separated by our visual system, the perception of colour is related to the light level. The amount of light (number of photons) reflected by a surface will depend not only on the spectrum of the surface and the light source, but also on the intensity. Thus, light levels might have impact not only in colour appearance but in colour preference too (Wei, Bao and Huang, 2020).

In fact, luminance can carry a lot of information and it is, indeed, needed to describe a colour. “In flat diagrams luminance is absent, hue is represented as position around the circumference and saturation is represented on distance from the centre. You might argue that, in describing colour, luminance isn’t important compared with hue or saturation, but luminance alone accounts for the difference between yellow and brown” (Livingstone, 2014, p. 65).
As Margaret Livingstone explains, the colours in a painting will change depending on the light level, but “understanding luminance is also important for our perception of depth, three dimensionality, movement and spatial organization. These visual processes respond only to luminance differences and are insensitive to colour” (Livingstone, 2014, p. 31).

2.2.3. It’s all about contrast

Visual contrast is the ability to distinguish an object’s (or image’s) luminance or colour from their background or adjacent entities. Biologically, humans are interested in information about surfaces around us, not about the nature of what is lighting them. Thus, human vision is able to adapt over a huge range of light levels (around 100,000-fold) and wavelength compositions of the illuminant. Besides, due to what is called centre/surround organization of its cells, different perceptions of the visual system are more sensitive to discontinuities than to absolute levels, where neurons respond better to abrupt changes than to gradual shifts (Livingstone, 2014).

In Clifton Taylor’s words: “Our visual system has a preference for contrast and will seek it out and enhance it when possible. We do this with both dark and light contrast for monochromatic palettes, and colour contrast for polychromatic palettes. This phenomenon is responsible for the apparent saturation of very pale compositions where very little real contrast is present” (Taylor, 2019, p. 99).

Multiple types of contrast can be defined. According to Itten, there are seven kinds of contrasts, including light-dark (which would correspond to luminance), hue, saturation, simultaneous or complementary (Johannes Itten, ed. 1973). This work was based on pigments and an artistic perspective but can apply to, or be affected by, lighting.

It could be said that, in perception, contrast is one level above than colour and luminance. The degree of difference between adjacent elements will dictate how strong is the perceived effect, either it is colour, luminance or both.
2.3. Colour metrics: CIE representation, Colour temperature and Colour rendering

2.3.1. The CIE colour space

As an evolution of colour circles, the Commission Internationale de l’Eclairage (CIE) created, in 1931, a two-dimensional map of colours to express any colour on our hue plane and, adding a third dimension, its position along the luminance axis. The chromaticity coordinates (x,y) define the two-dimensional position while the luminance is referred to as Y; these parameters can be related to the response of our cones and how our visual system process these responses. This chart is still widely used and referred to as CIE 1931 xy or CIE XYZ 1931 colour space.

![CIE 1931 xy vs CIE 1976 u'v']


There are various versions of the CIE chart. The CIE 1960 UCS (u,v chromaticity coordinates) was developed for additivity rules of the lighting industry, which then was converted into the CIE 1976 u’v’ chromaticity diagram, CIE 1976 UCS or simply CIELUV. This version improved uniformity by the transformation $v' = 1.5v$ (Miller and Royer, 2013), and it is considered appropriate to measure light sources as it keeps perceptual distances between colours (Schanda, 2007), allowing the plotting of additive mixing of two or more colour -see appendix A-.

CIE colour space charts are graphs of all possible visible colours. This is true only as regards a certain level of luminance, these charts assume the full output of a given source but reducing this output will result in a colour shift. There are colours that exist in the world of pigments and in nature, such as brown or grey; when dealing with light, we see that these colours are reduced output versions of colours that exist in the CIE chart (Taylor, 2019).

The CIE colour space can be a good starting point to predict colour of a light source although they suffer from multiple drawbacks (Besenecker, 2016). CIE charts can still be used as a tool to understand and predict how a multiple colour LED light might look, as well as what colour spaces can be generated from a fixture. In fact, narrowband wavelength emitters correspond to (spectral colours) highly saturated hues which theoretically, do not shift as the intensity decrease.

2.3.2. CCT, Planckian locus and $D_{uv}$

Colour temperature (CT) is expressed in Kelvin [K], and defines the colour of a light source compared to that of an ideal blackbody radiator (Planckian radiator) at temperatures roughly between 2,700 and 10,000K (Schanda, 2007). Each CT corresponds to specific coordinates of a colour space, while the path formed by those points is called Planckian locus, or black body locus (Planckian locus, 2020).
Figure 11. Planckian Locus with isolines from 2000K to 10,000K (1,000K steps, starting top right) and 10,000K (bottom left) in the different CIE charts. Data from Donald Schelle (Schelle, 2012).

If the chromaticity coordinates lie exactly on the Planckian locus the term Colour temperature is used. If the chromaticity coordinates of the source differ slightly from the Planckian locus, it can still be compared but is expressed as correlated colour temperature (CCT) instead. The CCT points are part of the corresponding CT’s isoline, that is, the closest point on the locus. (Schanda, 2007).

Figure 12. CCT and Duv are still calculated in the CIE 1960 (u,v) diagram aka (u’, 2/3v’); although this diagram is considered generally obsolete.

The distance from the CCT point to the locus is denoted as Duv. It is valid to speak of a certain CCT (compared to the corresponding CT) if $D_{uv} < \pm 0.05$ (CIE, 2004). This value often not present in specifications and defines the “tint” of a “white” source: $+D_{uv}$ values would correspond to “green tints” while $-D_{uv}$ values would correspond to “magenta tints”.

CIE recommends both the $(x,y)$ and $(u’,v’)$ chromaticity coordinates for light sources, but: “when chromaticity differences of coloured lights are evaluated $(u’,v’)$ should be used because these are significantly nonuniform in the $(x,y)$ diagram” (Schanda, 2007, p. 107).

However, two different CCT and Duv points do not describe colour difference. In CIE 1976, yet another metric $D_{u’v’}$ deals with this issue (Miller and Royer, 2013).

### 2.3.3. Rendering metrics, why we need something else

The complex technical solutions for highly demanding environments in terms of light quality and perception, such as theatres and museums, are lacking a common language that designers, technicians and manufacturers can share. This is a problem when these industries are forced to invest in order to move towards more efficient solutions.

All rendering metrics, and colour metrics in general for that matter, have their pitfalls, especially when it comes to standardising and representing how human perception behaves; although measurements allow us to have objective references.

For example, CRI has been (and is still) widely used over the last decades, but it has shown its limitations, especially with the advent of LED narrowband sources (Lighting Research & Technology, 2015) (Smet, David and Whitehead, 2016). CRI is considered outdated (Taylor, 2019) and has led to misunderstandings, holding back development of products (Royer, 2016).
TM-30-18 has overcome most of these limitations providing comprehensive information about colour rendering of light sources (EERE, no date) but it is complex and relative, especially for colour mix fixtures.

2.4. “White light”, metamers and how to get there

The concept of white light is tricky. White is a non-spectral colour, that can only be formed out of mixtures of other wavelengths. There are probably infinite combinations to achieve a particular white or its different versions. It could be said that the “purest” white would be an equal mixture of all visible wavelengths, where sunlight is probably the closest existing source to white light.

“In most natural forms of light - sunlight, moonlight, or firelight - billions of distinct frequencies mix together to make what we call ‘white light’”. (Taylor, 2019, p. 12)

A full spectrum source is one that produces all the wavelengths of visible light, including traditional tungsten, or the halogen light bulbs, that have dominated lighting industry for many decades. However, it is important to understand that not all the wavelengths are output in same relative proportions for different full spectrum sources.

Due to the additive nature of colour mixing, there are many ways of reaching versions of white light: mixing a pair or complementary colours, any two secondary colours, three primaries or more complex colour mixes. Generally, all different CCT values are considered versions of white light.

Moreover, if we don’t have a reference our eyes normalize the white that we have, after some adaptation. Our sensation of white depends on viewing context and duration, which determine the relative output of the visual channels, rather than on the physical characteristics of the source (Rea and Freyssinier, 2013).

2.4.1. Metamers

“Spectrally different colour stimuli (light reaching the eye) can have same tristimulus values (i.e. chromaticity coordinates) in a specified colorimetric system, and this is called metamerism and the colour stimuli with the same tristimulus values are metameric colour stimuli or metamers” (Schanda, 2007, p. 70).

Human visual system cannot distinguish if a sensation of colour is caused by a single wavelength or a mixture of wavelengths as long as excites each of the three cones in the same ratio (Livingstone, 2014). This behaviour renders possible the existence of metamers.

Hence, when there are more than three colours in a colour mix system, there will be more than one way to obtain a visually equivalent match from different spectral compositions -see appendix A-. Technically, increasing the number of emitter colours in a luminaire, the number of possible metamers is increased (Taylor, 2019).
2.5. Complex LED colour systems

“Because we were working mostly with white sources (filtered for colour), we came to think of colour as being somehow separate from the light... Full colour mixing LED sources reveal this way of thinking about colour to have limitations” (Taylor, 2019, p. 10).

The most basic version of LED colour mix is RGB - Red, Green, Blue- and this may well be enough for certain applications. However, the need of paler tones, vibrant colours, fine-tuneable white points or filling of spectrum gaps inherent to colour LED fixtures (individual LEDs emit in very narrow bands ≈ 30nm) has forced the lighting community to develop more complex colour systems. These systems might not currently have the continuity of spectrum of other sources, but, as Robert Gerlach points out, they offer great possibilities for creativity and exploration beyond the use of saturated colours (Besenecker, 2016).

Complex LED colour mixing offers new possibilities to mix and match equivalent appearing colours. One example is that RGB colour mixed conditions are not able to match the saturation of narrowband cyan or amber LEDs; another example is the rendering of deep violet colours, that were not easily possible with tungsten due to low energy in the short wavelength region (Besenecker, 2016).

Clifton Taylor summarizes one of the main ideas of the present study in relation with Multi-LED systems: “Each source of light that we work with creates its own colour space and offers the possibilities of creating unique colour mixes. So, instead of getting wrapped up in finding colours equivalent to those made with one kind of light, perhaps it would be interesting to explore what new colours are possible with various sources of light” (Taylor, 2019, p. 131).

2.6. Lighting design approaches in exhibition environment

Methods for museum lighting always communicate a conceptual approach to art, even in situations where curatorial attitude aims to be neutral. Thus, several questions arise in order to achieve a “suitable” lighting concept. Lighting designed for exhibitions is frequently linked to an extensive design process with architects, curator, conservators, lighting designers and, of course, artists and visitors; all with their own demands (Schielke, 2020). “The nature of lighting is inseparable from the visual experience of art” (Cuttle, 2007, p. Preface)

On the other hand, the role of museums has shifted towards the visitor perception and experience (Schielke, 2020); the lighting industry is thinking of new methods of illuminating art pieces in order to adapt to the changing nature and behaviour of visitors (Maccheroni, 2018). New approaches, such as the Monza Method (Iannone, 2017), or the use of dynamic changes of colour temperature recreating various phases of perception in front of a painting (Maccheroni, 2018), aim to avoid “museum fatigue” and improve visitors experience (Maccheroni, 2018; Hurlbert and Cuttle, 2020; Schielke, 2020).

At the time of writing, the world is living a pandemic situation and it seems clear that, at least in the near future, museum experience will change drastically. The director of the Reina Sofia museum in Madrid says on this: “Perhaps exhibitions should be planned differently and think more about investigation” (Borja-Villel, 2020). One of consequences will be the limited number of visitors at any given time, which present a good opportunity for increasing customized visitor experiences.
2.7. Energy efficiency and conservation in the background

There are multiple factors to consider when designing lighting for an exhibition, but conservation and energy efficiency appear as critical factors in terms of sustainability for both the art and the planet.

In regard to conservation, light absorbed by objects turns into heat and can damage pigments and deteriorate artefacts even if IR and UV radiation are filtered. Thus, absorbed light must be minimised while maintaining the colour appearance required for the appreciation of the artwork (Durmus et al., 2020). Again, the discussion might go on about different lighting design approaches, but studies have shown that narrowband LEDs can be used to rejuvenate the appearance of aged colour (Viénot, Coron and Lavédrine, 2011), or optimized to minimal damage and maximal colour quality (Schanda, Csuti and Szabó, 2016).

There might be discussion about lighting quality and adequacy of LEDs for quality demanding applications, but there is no doubt about the convenience of switching to LEDs in terms of efficiency. In theatres for example, the energy savings do not correspond only to the light produced but also to HVAC on buildings in response to the heat generated by traditional sources.

As Robert Gerlach explains, LEDs deliver more light for less power, but quality is critical for theatre and museum environments where thinking only in terms of lumens per watt is not desirable. In fact, this is a problem not only for designers but also to manufacturers as it is often out of reach to meet standards and fulfil quality and fuller spectrum requirements (Besenecker, 2016).

Another key concept in terms of efficiency, is the fact that in LED colour mixing, colours are created by adding light, rather than filtering (i.e. tungsten, discharge or single LEDs).

On yet another facet, a wider spectrum might be beneficial in terms of quality, but the fuller the spectrum the lower the efficacy. Thus, using narrower bands and less broad spectrums not only opens new perspectives in terms of creativity but also in terms of sustainability.
3. METHODOLOGY

3.1. Two sides of the experiment

One of the motivations of the present study is to demonstrate the opportunities that complex colour LED systems offer for specific applications such as theatre and exhibitions. In this context, the experiment focuses on two perspectives. On one side, the creation of metameric conditions to create light scenes which produce virtually identical measured values (CCT, \(D_{uv}\) and Illuminance) but have different effect in the appearance coloured surfaces. Additionally, extended CRI and TM-30-18 were measured to have quantitative measurements of colour rendering.

On the other side, the exploration of how different colour mix light conditions can modify the perception of colour on two different paintings. In order to have a qualitative assessment, these conditions were photographed, serving as basis for an online questionnaire which aimed to underline the importance of lighting for the presentation and interpretation of art.

3.1.1. Special conditions of the experiment

Being in a pandemic situation has influenced the way this thesis was approached, especially in its experimental procedure. Hence, it has to be considered that the experiment was performed in a “home lab” situation where some conditions were not ideal. In fact, it would have been interesting to set up a small exhibition, where people could have visited and experienced the artworks live. Nevertheless, it was decided to craft an online survey which added extra “in-between layers” that modify the perception such as photography, compressing colour profiles or different screen and devices. At the same time, the digital and non-physical nature of the experiment presented new perspectives and challenges that would have otherwise been omitted.

3.2. Exploring metamers and its application

3.2.1. Experiment rig

Despite the situation with COVID-19 at the time of this writing, it was possible to set up a meaningful study thanks to contributors already acknowledged.

![Figure 14. Two profile light sources were positioned side by side, each it two consecutive spaces on a white wall in order to have a visual reference for comparison. Both fixtures had same relative angle and distance to the wall. An ETC console allowed independent control of each fixture via DMX. Wall and floor were marked to have same positions throughout the experiment.](image)

![Figure 15. Left: Image of setup with a painting in position L. Position R was only used for reference on different tests; Right: Actual experiment condition with painting and spectrometer in their L position. All measurements and pictures were taken using this configuration with no ambient light.](image)
Despite the many factors that can influence the perception of an illuminated art piece and, thus, many different configuration approaches, the choice was to have a completely dark environment where the only light source is the one used to light up the painting. The focusing and framing of the light beam was kept so that the background is barely illuminated to avoid as far as possible its influence in the perception of colours.

All measurements were performed with a Konica CL-500A spectrometer and data extracted with the Konica CL-S10 application. Although it is not possible to measure colour “as we see it” (Besenecker, 2016) the measurements help to establish an objective foundation for the experiment.

3.2.2. The light source: seven colour system by ETC

The fixture used for the experiment is an ETC source four LED Lustr, which provide a complex colour mix system with seven different sets of colour emitters (Indigo, Blue, Cyan, Green, Lime, Amber and Red as commercially named). Two diffusers were used, before and after the lens tube (36°) to provide a more uniform mix of colours and softer edges on the beam.

![Figure 16. ETC Source four LED Lustr with lens tube 36° (Right); LED emitters configuration projected on the wall without both, lens and diffuser (Left).](image)

![Figure 17. Spectral distribution of the fixture’s colour emitters as measured by CL-500A. All emitters were measured individually at full power, peak wavelength for each emitter indicated in nm.](image)

![Figure 18. Emitters’ chromaticity coordinates on the CIE1976 as measured by CL-500A. Left: plotted versus monochromatic outline of the colour space; Right: plotted vs representation of colour space. Data extracted from Konica excel template and colour background image of public domain (User: Adonisick, 2008), edited in Vectorworks](image)
3.2.3. The lighting subject: Artwork painting

Two paintings by Spanish artist Carmen Catalán have been chosen as lighting subject. According to the artist, the pieces were painted onsite in a late spring noon in the North East of Spain. *El olivar* portrays a vision of an olive tree garden, while *Pasión solar* depicts a more poetic representation of the sensation of being under the same tree. Both paintings were created with watercolour on paper.

Light scenes were built for the first piece, as it allows for the production of more diverse results in terms of depth, scene lighting and atmosphere. The latter piece offers a more varied colour palette, and it mainly helps to contrast aesthetic results on an artwork of different characteristics.

*El olivar*

![Figure 19. "El Olivar", Carmen Catalan (1991) illuminated by LS1 (defined later)](image)

This painting is composed of a, mainly, green palette on the foreground of the scene against some lavender and warmer tones in the background. This composition offers the possibility of bringing the two grounds back and forth and experiment with the hierarchy of warmer versus colder tones, modifying the perception of light in the scene (i.e. coming from behind or the front) or the season and time of the day association.

Lighting and atmosphere can be modified by considering contrasts; there is room for subtle contrast within monochromatic palette areas (leaves), as well as within the bright/dark areas of the tree trunks. These trunks are important because, together with the purple tones of the background, can modify the perception of distance between the trees and spatial perception of the scene.

*Pasión solar*

![Figure 20. "Pasión solar", Carmen Catalan (1991) illuminated by LS1 (defined later)](image)

This painting is a poetic close-up vision of the same tree as the previous piece. The author was “amazed by her changing perception as she came under the tree”. Here we find a more polychromatic palette where there is a possibility to experiment with vibrancy and the contrast between polychromatic palettes. Purple and lavender tones oppose and contrast to yellow tones as well as reddish tones which oppose the greens of the leaves.

The painted scene here is more about colour and light than depth or atmosphere. By enhancing yellow tones, it is possible bring forward light on the centre of the painting and define the leaves differently according to the amount of green. Besides, having these opposed palettes gives the possibility of enhancing colours not by just raising its corresponding emitter tones but by modifying its complementary.
3.2.4. Daylight as a reference?

Daylight is very often used as reference for adequate lighting due to its continuous and full spectrum. However, the nature of daylight is changing constantly depending on the weather conditions, time of the day or location.

For example, sunlight contains all visible wavelengths and its peak wavelength above the atmosphere is at around 500nm, corresponding to a colour temperature of 5900K (Liew, 2001), but the colour temperature might vary significantly between sunrise/sunset and overcast days (Poirier, Demers and Potvin, 2017).

Due to this changing nature of daylight, it is difficult to think about a neutral condition that an artist may have had at the time of painting. With another twist; what would be more adequate? to enhance the vision that the artist had at the moment of creating the artwork (if known) or to “neutrally” illuminate the painting? In any case, the perception and of a viewer will be influenced and, possibly, trigger other associated feelings. The Monza method used in Palazzo Farnese in Rome addresses this question (Iannone, 2017).

3.2.5. Let’s be neutral, say 4000K

As discussed, it is arguable what would be a “neutral white” light but, within the CCT range, 4000K seems to be accepted by most as a neutral temperature. Besides, it is a challenging colour temperature as it lies between the CT of traditional tungsten sources daylight, both commonly used as basis (i.e. standard or reference illuminants) for colorimetry as in CIE systems, CRI or TM30.

The experiment aims to create a series of light stimuli (Light scenes) with virtually identical chromaticity coordinates, and as close as possible to the CT point within the Planckian locus on the CIE 1976 colour space. To be strict, metamer should have the exact same chromaticity coordinates, but such accuracy is more of an ideal situation. All devices and methods used in the experiment, including the spectrometer, are likely to introduce errors. Thus, for the purpose of this experiment, the values within the following ranges are considered metamers of the base values of choice:

<table>
<thead>
<tr>
<th>Illuminance = 370 ± 5 lux</th>
<th>Chromaticity coordinates:</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCT = 4020 ± 10 K</td>
<td>(x,y) = 0.3975 ± 0.005, 0.3765 ± 0.015</td>
</tr>
<tr>
<td>Duv = 4020 ± 10 K</td>
<td>(u,v) = 0.2250 ± 0.005, 0.5025 ± 0.015</td>
</tr>
</tbody>
</table>

Figure 22 These ranges are within perceptually negligible range in CCT and Duv (Ilmenau, 2007), and well below ANSI and Energy star recommended acceptable values for differences in specifications (LEDyi lighting, 2019).
Initially, five light scenes [LS1-LS5] were created according to these parameters. Thus, the fixture’s LED colours played at different ratio of intensity for each of the scenes producing five different metameric conditions. In spite of CRI flaws explained in the background section, an additional scene [LSCRI] was created. In [LSCRI] the only goal was to obtain the highest possible CRI and it was included in the investigation for comparison purposes. For complete measured data of the light scenes and resulting illuminated painting images -see appendix B and C-.

In each scene, the starting point was a different combination of three or four colours, minimising the use of the rest. By using this method, the capabilities of a seven-colour system are misused, but the aim was to demonstrate differences on the light stimulus rather than looking for an “ideal” lighting. Moreover, it helps to understand the potential of such a system if these limitations are removed. Translating this concept to a real-life application the colour modifications can range from subtle to significant in order to fit a specific lighting subject or concept.

It is worth noting that, as expected, not all the emitters had the same impact in the perception of colour and luminance. For example, the lime emitter had great impact in terms of live perception and measured brightness, as its relatively wide band hits the highest sensitivity range of human vision.

3.3. Preparation of the survey

3.3.1. Dealing with the images

One unexpected source of experimental controversy in this study was the photography of the results. Originally, photos were planned to be used just to illustrate the process and give an idea of the outcome. However, conducting the experiment with no other test subject required having to translate the evaluation process into a digital environment for the online survey. This posed new challenges adding layers of complexity to the study.

The first step in order to go digital was photography. The subjectivity of human colour perception has been discussed, as well as the different perspectives of art displays and lighting designs. In addition to this, capturing reality in photographs requires subjective decisions even if the aim is to be as neutral as possible.

Pictures of the illuminated paintings were taken with a Sony α7R II, fitted with a 28-70 mm lens. All automatic settings on the camera were disabled in order to have consistent capturing setup throughout each lighting condition. Furthermore, the photos were exported from .raw format into .png using sRGB colour profile and same settings for all the images. The software used for this process was camera raw from Adobe Photoshop.

3.3.2. The survey

An online survey was conducted using the Google Forms platform which added extra limitations since the images had to be reduce in both size and resolution. Moreover, the online nature of the survey adds new layers to the “neutrality discussion”, since it is not possible to establish what devices or screen calibration are used by the viewer.
The questionnaire -see appendix C- was sent to individuals with a relationship to the topic and of a wide variety of nationalities and backgrounds, although the data was anonymously collected with no demographic questions. Participants’ background varied within creative and design fields such as art, music, graphic design and photography, lighting, audio-visuals, architecture or interior design. A total of 58 responses were collected.

The questions aimed to evaluate the different perception of the paintings caused by different lighting scenes \([\text{LS1-LS5 and LSCR1]}\], addressing colour theory topics as well as subjective impressions. The six lighting conditions for each painting were presented in plates, so that they could all be seen at once -see appendix C-. Additionally, it was recommended to zoom in for particular details of each image.

Besides, the technical difficulties mentioned earlier, post-survey comments mostly agree it was an interesting investigation but highlighting the fact that it was difficult to “decide objectively”. 
4. RESULTS AND ANALYSIS

4.1. Light scenes composition

The following page shows a summary of visual and measured output for the main 6 scenes LS1-LS5 and LSCRI -See appendix B for complete measurements and appendix C for larger image plates images-. It can be observed how LS1-LS5 have, in practical terms, identical CT, Duv, illuminance and CRI values but the ratio of intensity (DMX value) of each set emitters (meaning one colour) varies significantly from scene to scene.

LS1 was essentially created keeping all the emitters as default, with minor adjustments to reach target values. LS1 & LS4 were created starting from two different sets of colours: RGB with some amount of lime in LS2; and amber (A), lime (L), Indigo (I) with a bit of blue and red in LS4. The same approach was used for LS3 & LS5, but instead starting from two different sets of 4 colours (A, G, C, B vs R, L, G, I) with green as the common colour (corresponding to El olivar’s main colour palette), and minimal contribution of the rest of colours.

Creating a high CRI was simply achieved starting from fixtures´ default 4000K, by just adding some lime and amber to fill gaps found in the dark greens and warm hues as compared with the reference illuminant. Interestingly enough, searching for a high CRI resulted in a CCT close to the ideal value of tungsten, 3200K.

4.2. Light scenes analysis

4.2.1. Virtual metamers

As explained earlier, light stimulus [LS1-LS5] created are considered metamers as they plot to virtually same coordinates -see appendix B for complete chromaticity coordinates and expanded graph-. LSCRI is shown as a reference (CCT = 3200K ; Duv = +0.004).

![Figure 24. Example of DMX values for a scene (LS3) extracted from ETC Colour Source 20 software. DMX values (0-255) control the intensity of each set of emitters corresponding to a colour in the fixture. Figure 25 shows DMX values for all the light stimulus, that is, the amount of each colour on the mix.

![Figure 25. Light stimulus LS1 to LS5 plot on the CIE 1976 chart. Full colour space (left) vs. zoomed in version (right). Further zoomed in view in appendix B. It can be observed that LS1 to LS5 plot virtually to the same coordinates at these scales (see appendix B for a larger zoom in). LSCRI stimulus can serve as a comparison distance to the locus is proportionally one-fold bigger than the metameric conditions.](image-url)
4.2.2. Light scenes output

Figure 26. Summary of measurements and resulting images of the painting for each of the light scenes.
In spite of its limitations and the discouragement about its use, extended CRI was measured as a reference to traditional colour metrics.

4.3. Survey analysis and the artist view

Following the experimentation with colour mixing in light, and its quantitative measurements; this section focusses on the subjective experience of both artist and viewers.

Painters also explore colour. Although their colour mixing is subtractive since it is based on pigments, colour and light are still inextricably linked.

On the other side, the viewers’ perception is analysed qualitatively from the results of the online survey -see appendix C-. The variety of answers recall the subjectivity of human perception, but also provide relevant common patterns.

Carmen Catalán was interviewed regarding the intentions of the pieces and her view on the resulting scenes (From the images posted on the survey). This is relevant point for the investigation as it relates to the concept of the “original intentions of the artist”.

According to her view of El olivar, LS1 connects more to the visual and symbolic memories at the time of creation. On the other hand, LS2 seems to her the closest to the way she has observed the painting over the years, probably due to colder tones produced by indirect illumination from both natural and artificial light. Carmen also pointed that LS4 improves the feelings that she was aiming to transmit and would probably choose it for an exhibition nowadays.

For Carmen, Pasión solar does not represent reality, it’s more of an “oneiric” view. Again, LS1 represents the image that she has of her painting after the years. Besides, LS1 is her preferred choice aesthetically as it transmits “a warmth solar light and the chipping of birds” and connects to the symbolism which motivated her for this artwork. The artist added an additional comment on LS4, as she considered it triggered her imagination on another “dreamy” feeling to the scene.
4.3.2. Survey responses: Scene 1 [LS1]

For *El olivar*, LS1 rated the highest in terms of preference (26%) and naturalness (35%), due, according to survey’s open question (Q2), to its resemblance to nature and its “balanced” and “equilibrated” colours. This can be explained by the use of all colours in, almost, equal proportion (this implies a good fixture colour system design). Conversely, this scene was not amongst the most highly voted on brightness, vibrancy or contrast.

Despite good results in naturalness, LS1 was not widely chosen (11%) in the direct question as the most similar to conditions in which the painting was created, although it was often defined as morning/noon or spring/summer.

LS1 also rated top in preference (22 %) for *Pasion solar*, although the results in this category have a relatively even distribution (≈ 18% ±4%) for all the scenes at 4000K -see figure 30.-

4.3.3. Survey responses: Scene 2 [LS2]

LS2 got the lowest percentage (≈ 10%) for *El olivar* in the majority of the questions, which is logical considering that the scene was RGB based. However, it performed well in terms of depth (17%), probably since it gives hierarchy to the warmer and lavender tones of the background; although results on this aspect were, again, relatively uniform (≈ 17% ±7%). Despite its discrete results, it still was mentioned by some participants as looking closer to their impression of nature.

Conversely, LS2 obtained the most significant results in terms of representing a different time or season, as it was very often mentioned as having a dusk, cold weather or even “wintery” feeling to it “albeit leaves on the tree”. For *Pasion solar*, this scene gained relevance in, basically, all the aspects; including preference. The only aspect that rated the lowest, just as with *El olivar*, was vibrancy.

4.3.4. Survey responses: Scene 3 [LS3]

In this case, *El olivar* results were prominent only in terms of brightness (22%) and depth (24%), while remained low for rest of the parameters. This scene was also described as “colder” suggesting a shift towards colder periods (autumn, evening) or locations. For *Pasion solar*, this scene presents a low profile in the responses, except from brightness in which holds near the most selected.

These results can be explained due to the predominance of amber emitters in the colour mix, which brings forward the background for *El olivar and* enhances the sense of brightness in *Pasion solar* due to the predominance of warm tones in the palette.

4.3.5. Survey responses: Scene 4 [LS4]

LS4 ranked very high at various parameters for *El olivar*. Chromatic range (35%), contrast (29%) were the most significant. Also, it was chosen as the most resembling the time and season in which the painting was created. As for LS1, it was referred in the open question as being closer to the impression of nature and having a good balance in colours and hues.

*Figure 29.* Measured spectral distribution of LS4 (see appendix B for all measured SPDs) shows a reasonably flat distribution in the middle frequency range which correspond to the highest sensitivity of human vision and the majority of spectra in *El olivar*. This would explain significant results obtained by this scene, although its limited number of colours in the mix.
LS4 was clearly the most relevant light condition for Pasion solar, since it obtained the highest score for all the questions; especially for contrast (36%) and vibrancy (45%).

4.3.6. Survey responses: Scene 5 [LS3]

LS5 had overall good comments for El olivar, mainly in the non-technical aspects such as naturalness, preference and resemblance to nature. Besides, mentions in the open question were constant about being balanced and with a good level of saturation, being mostly defined as summer and noon. Some people characterised LS5 as an in-between LS1 and LS4, which might have masked its relevance.

For Pasion solar results are more discrete. This is probably due to an over saturation of yellow and greens caused by the predominant colours in the fixture’s colour mix.

4.3.7. Survey responses: Scene CRI [LSCRI]

For El olivar, this scene triggered significant perceptions in factors related with colour and luminance such as vibrancy (35%) brightness (35%) but moderate on chromatic range (18%) and spatial perception (depth). Moreover, it was the least chosen for naturalness (4%), and one of the lowest in preference (12%). In the open question, the scene was regularly suggesting a dawn daylight phase, warm feelings, and related to a late summer/autumn season.

For Pasión solar the questionnaire yielded similar results and was clearly the least chosen in terms of preference.

4.3.8. Summary

Generally, Pasión solar yielded less obvious results agreeing to the feeling of El olivar being more suitable for changing parameters affecting perception. In practice, these results acknowledge the fact that same lighting condition might have different effect depending on the lighting subject.

In this respect, results with negative connotations are equally interesting, as they help to understand that even the slightest colour modifications of white tuning can lead to losses on particular aspects of art perception and interpretation.
For example, a certain colour can be enhanced not only increasing the intensity of a colour matching its spectrum, but also reducing the amount of complementary as it will unbalance the mix to white produced on a specific pigment or surface. It is worth clarifying that this is opposite to the idea of enhancing a colour (light or surface) by placing its complementary adjacent to it; the difference in this case is that colours do not mix.

It is important to note that analysis of results obtained by this type of survey should be taken with caution, as they are influenced by many factors other than lighting, such as photography, quality and configuration of screens, and personal contexts. Nevertheless, the author considers that the number of participants is relevant for the investigation, rendering the results valid for discussion purposes.

Post survey feedback generally reported the survey as “interesting” and “difficult”, as participants found it complicated to objectively decide about their interpretation of the questions and response choices.
5. THE INVESTIGATION IN CONTEXT

Probably, one of the main outcomes of the survey is the subjectivity of human perception, particularly when it comes to vision, colour and art. This idea was expressed by Clifton Taylor: “colour preferences by an individual artist or designer are subjective and open to interpretation” (Taylor, 2019, p. 19). On another interview Clifton also says: “colour is an expression of culture and can be tied to periods of time, technology, and local natural environment” (Besenecker, 2016).

5.1. Original intention of the artist, being “neutral” and the viewer interpretation

As mentioned previously, the idea of respecting the original intentions of the artists are often found in guides and catalogues for museum lighting. However, knowing the artist intention or the conditions in which the painting was created is not always possible as it is in this study. Even when this is possible, it can be hard to agree on perception, personal impressions or feelings.

Having said this, the survey showed trends regarding the interpretation of the painting. Half of the participants found LS1 or LS4 as the closest to the representation of the painted scene and their impressions of nature: the same scenes were pointed by the artist as most relevant to her upon the same concepts. She was satisfied to see “how lighting could reveal or enhance sensations only felt at the time of creation which otherwise are lost”.

Another repeated concept when lighting an art piece is that of being neutral. This study implies the difficulties of the concept. For example, Margaret Livingstone says: “There is no absolute ‘correct’ but if you want to see what an artist saw while painting a picture, you should view the painting under the same light the artist worked on” (Livingstone, 2014, p. 37).

The creator of the Monza method elaborates on the idea: “The demand for illuminating neutrally, have not considered that this neutrality had never existed before [...] and works were not meant to be shared at neutral levels: apart from the fact that neutral light does not exist” (Iannone, 2017).

Based the physics of human vision and neurological and cognitive research, the Monza method builds on the idea of lighting applied in an interpretative sense, focussing on the viewer rather than the work itself: “light, both natural and artificial, supports our interpretation of reality” where “lighting was geared to the ‘needs’ of the painting and not dictated by engineering considerations” (Iannone, 2017).
The survey also showed that all the scenes generated different interpretations for different participants in terms of perception and personal triggers. This does not mean that “any lighting will do, and someone will like it”. The same way that artists have use techniques to play with colour, luminance and contrast in order to impact viewer’s experience (Livingstone, 2014); knowing the possibilities of complex LED colour systems for lighting design broadens the perspective to modify or enhance the perception and interpretation of art.

5.2. Dynamics and customization

Recent articles already consider dynamic presentations of the artwork, in combination with daylight, or creating different phases of perception by slowly changing the colour temperature or sequences of colour (see e.g. Maccheroni, 2018; Hurlbert and Cuttle, 2020; Schielke, 2020). These techniques can help to reduce “museum fatigue” facilitating a “narrative through the lighting”.

Another concept to explore is that of customization. As example, a viewer could choose between pre-set scenes to modify, for instance, the viewer’s notion of daylight in a painted scene. This would allow the visitor not only to appreciate different details but would improve the experience and engagement to the art pieces.

Complex colour LED systems offer possibilities to the different visions of actors involved in the exhibition environment, where lighting designers can adapt the spectra to the lighting subject with flexibility, artist can dynamically present their artworks (Schielke, 2020) or curators can adjust light and colours of the painting to their needs (Schanda, Csuti and Szabó, 2016). On a more commercial perspective, it would not be unreasonable that galleries sell art pieces with accompanying lighting solutions; and these could include customized presets for an enhanced experience.

The appendix B (‘two extra scenes’) offers an additional view on the opportunities, but also on the risks of colour mixing techniques.

5.3. The link to theatre

Although theatre differs from painting in a number of aspects such as three dimensionality, movement or atmosphere interaction; some of concepts and methodology used in this study could be translated to investigate the theatre environment such as the rendering of pigments in scenography backdrops, materials, costumes, make-up or skin.

In a more conceptual way, theatre and paintings both have a “scene” (painted or represented live) observed by a viewer outside the scene, where lighting concepts implemented for a painted scene could serve a basis for a stage set in terms of composition, hierarchy or contrast.

In theatre environments, the use of complex colour LED systems also offer great opportunities in terms of accurate colour rendering requirements.
Traditionally, one could estimate how a tungsten lamp and certain filter will look and render; with LED technology such estimations are not possible, unless the same specific fixtures are planned. Moreover, these systems allow for quick and live adjustments of colour that might be required due to changes in production or colour shifts in the fixtures.

5.4. Limitations and further investigation paths

Out of the scope of this study, there are a number of factors that can influence metameric light conditions and the influence of fine colour tuning on colour perception of an art piece, in both the physical and the psychological realms. These could include, the influence of background and ambient light level (Feltrin et al., 2020), the differences in colour vision which affect metamers when using peripheral view (Besenecker, 2016), or the many aspects involved in measuring colour (Hunt and Pointer, 2011), to name a few.

In the museum lighting context, energy efficiency and preservation of the art is critical with some studies addressing this issue in conjunction with maintaining the colour appearance for the artworks (Durmus et al., 2020). In this respect, perhaps it would be interesting to investigate the viability of “video mapping” the art pieces. This would allow very precise colour tuning, while improving conservation and efficiency requirements of exhibition environments.

Another interesting thought for investigation belongs to the controlling edge (i.e. lighting consoles or control systems) of complex colour mix LED systems. As Mark Simpson introduces in an interview, console manufacturers can already provide metameric matches of colours (Besenecker, 2016). With further research, these metamers could be maximized to enhance or mask different parameters of human perception of colour in the arts.
6. Towards new models

Hopefully, the present study can provide guidance and motivate different approaches for the museum and theatre lighting design intent. Besides, entertainment and architectural industries are ever more merging technically and conceptually, where lighting solutions and concepts are shared and developed in both territories.

The underlying motif of this study is to explore the opportunities that LED technology, and complex LED colour systems in particular, are able to offer rather than getting trapped in their comparison with traditional sources. In fact, a bigger understanding of the complexity and possibilities of such systems would benefit a better communication between the stakeholders on the lighting industry, from authorities to manufactures and designers.

COVID-19 will change our social behaviour to an extent that is now difficult to predict. Thus, research and investigation become crucial for all areas of life allowing to respond to new circumstances. In museums, new models will have to be devised to continue improving the visitor experience in both the physical and virtual realms.

This pandemic situation has also accelerated an existing shift in the paradigms of exhibition environments, where institutions have boosted their digital programs as a complementary experience to the physical enjoyment of the art, allowing the creation of a narrative and context that can fulfil clients’ contemporary demands (Zwirner, 2020).

In any case, lighting will, again, have an essential role to play.

“The same way that light is a material for architecture, colour is a material for emotions.”
Appendix A. Colour mixing on the CIE space

Estimating colour spaces

In the CIELUV chart, colours of the light sources can be plotted, and their relative distance measured $[D_{UV}]$. In addition, once a group of colours are accurately plotted as chromaticity coordinates, it is possible to connect these points representing an estimation of the range of colours that occur by their additive mixing.

Figure 34: Left: estimation of a colour space for a seven-colour emitter; Right: Range of possible colour mixes between two complementary colours around a specific white point. These graphs are not, anyhow, based on official data from ETC, they are just approximations based on own measurements and calculations to illustrate theoretical concepts. Image for colour space background of public domain (User: Adonisck, 2008)
Metamers

Using this method, it is also possible to estimate areas of metameric conditions from different colour mixes. As explained, increasing the number of colours in the mix will increase their different potential combinations and, thus, the potential metameric conditions. Four, is the minimum number of colours in order to have metamasers in a colour mix as, at least, two different lines or areas have to overlap.

Figure 35. Different possible colour spaces to be generated out different colour combinations. Overlapping points/areas are possible metameric conditions which can be obtained from each pair of combinations: two sets of two (left), two sets of three (right top) and two sets of four (right bottom). These graphs are not, anyhow, based on official data from ETC, they are just approximations based on own measurements and calculations to illustrate theoretical concepts. Image for colour space background of public domain (User: Adonisck, 2008)
Appendix B. Light stimulus and measurements

DMX values

Scene 1

Scene 2

Scene 3

Scene 4

Scene 5

Scene CRI
Light stimulus’ chromaticity coordinates data

<table>
<thead>
<tr>
<th></th>
<th>Scene 1</th>
<th>Scene 2</th>
<th>Scene 3</th>
<th>Scene 4</th>
<th>Scene 5</th>
<th>Scene CRI</th>
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<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E'</td>
<td>370.9</td>
<td>371.1</td>
<td>369.6</td>
<td>372.0</td>
<td>367.4</td>
<td>369.2</td>
</tr>
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<td>x</td>
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<td>0.3791</td>
<td>0.3801</td>
<td>0.3794</td>
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<td>y</td>
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<td>0.3749</td>
<td>0.3780</td>
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<tr>
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<td>4016</td>
<td>4023</td>
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<td>4027</td>
<td>3222</td>
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<tr>
<td>dE(u)</td>
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<td>0.2250</td>
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<td>0.5018</td>
<td>0.5027</td>
<td>0.5021</td>
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</table>

Light stimulus LS1 to LS5 have been considered metamers. In real life, having metamers is more of a theoretical concept as measuring and lighting devices suffer from errors in accuracy and repeatability influenced by running times, temperature or variable experimental conditions.

Figure 36. Zoomed out version of chromaticity coordinates in CIE 1976. Light stimulus can be observed as different points, but this differences are far from being perceived by humans (Ilmenau, 2007).
Two extra scenes. “Seeing with my eyes”

In addition to the main light scenes created for the investigation, two additional light presets [X1 and X2] were personally explored. The purpose of these scenes was to illustrate the potential of LED colour mixing (with freedom about measurements) in order to produce more drastic changes in perception, and trigger imagination or different interpretations from the same art piece.

However, this exploration also serves to warn about potential risks if these techniques do not consider carefully the “needs” of the lighting subject, the concept or a specific application.

In this case, the scenes were adjusted according to the author of this thesis’ direct (live experience) perception of the paintings, in particular of the El olivar. The colour mix was created to communicate different interpretations of the painted scene, to add a more “dreamy” atmosphere with light coming from the background [X1] versus an enhancement of an hypothetical front light which would highlight the freshness and broaden the different green/blue tones on the leaves [X2].

The results help indeed to demonstrate both, the opportunities and the risks of colour mixing for art. In my view, both scenes worked nicely for the live experience. Additionally, also the artist saw an interesting concept on [X1] for El olivar, agreeing in the imagination triggers and the dreamy atmosphere.

However, these scenes also show that these experimental and exaggerated lighting conditions have to be used with caution. First, a lighting concept that might fit one art piece might not work for another one (as it can be seen here for Pasion solar). Secondly, the application or environment has to be considered, and some ideas that can be considered appropriate for a live experience might not work at all in a digital environment (as it is the case here with the photographs).
Appendix C. Survey Q&As (plates included)

El olivar [LS1-LS5 & LSCRI]

Q1. Which image of the painting appears more natural to you?

Q2. (Open question) Why?

Q3. Where do you perceive a broader chromatic range (wider variety of colours)?
Q4. Which scene looks brighter to you?

Q5. Where do you perceive a higher contrast/level of detail?

Q6. In which scene you have a bigger sense of depth (longer distance foreground/background)?
Q7. Which image seems more vivid/vibrant to you?

Q8. Which scene would you associate (from memory or imagination) with a Spanish end of spring noon?

Q9. (about interpretation) Does any of the scenes evoke a different time of day/season? (if so, write those that apply)

Q10. Which scene do you like most?
Pasión solar [LS1-LS5 & LSCRI]

**Q11.** Where do you perceive a broader chromatic range (wider variety of colours)?

**Q12.** Which scene looks brighter to you?
Q13. Where do you perceive a higher contrast/level of detail?

Q14. Which image seems more vivid/vibrant to you?

Q15. Which scene do you like most?

Survey available at:

https://docs.google.com/forms/d/e/1FAIpQLSdv2m-mRfVwqM_o5Il6sMKkqzWgAowzkLRoMHPvMW2mub8dsQ/viewform
REFERENCES/BIBLIOGRAPHY

Books


Johannes Itten (1973) The art of colour.


Papers/Publications


Ilmenau, C. (2007) ‘A Study about Colour-Difference Thresholds’, (Figure 1), pp. 1–11.


**Websites/Articles/Presentations/Catalogues**


**Image Sources**


Online survey

https://docs.google.com/forms/d/e/1FAIpQLSdv2m-mRfVwqM_o5Il6sMKqzWgAowzkLRoMHPvMWZub8dsQ/viewform