CREATING SCENES WITH LIGHT

An analysis of colour, distribution and LED in architecture and theater

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INTRODUCTION AND HYPOTHESIS

1. Introduction & discussion

This research paper is about the power of light to create scenes, in both fictional spaces and real, habitable ones: it explores the similarities and influences between theatre and interior architectural lighting, setting LED as the link in technology between the two. Taking as an example the time spent working in both realms, I find the relationship between both more than casual.
Starting with the fact that the first set designs in theater in the western world try to reproduce closely entire buildings and real life spaces (figure 1.1 & 1.2); "at one time the curtain went up and at a first glance the audience would gain and immediate impression of a royal palace, the castle or the drawing room". Bentham, page 23 (1). Of course this naturalistic representation has evolved along with contemporary artistic tendencies, becoming the current broad spectrum of possibilities, from the almost complete elimination of the set (figure 1.3) to the ever so majestic construction of the traditional set designs. In any case, it is always a relationship of a human being (the actor) with its surroundings, and the subsequent self-identification that happens from the viewer. And what is architecture based in, if not the human scale and its integration and relationship with the environment?
For instance, architecture in both public and (somewhat) private spaces is progressively looking for more creative and control based solutions, aided by

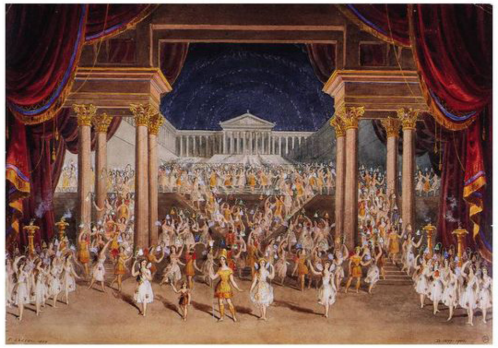


Figure 1.1: Set design : Dance of the Fairies, Palace of Theseus, Athens. A Midsummer night's dream. The Grieve family, 1800´s

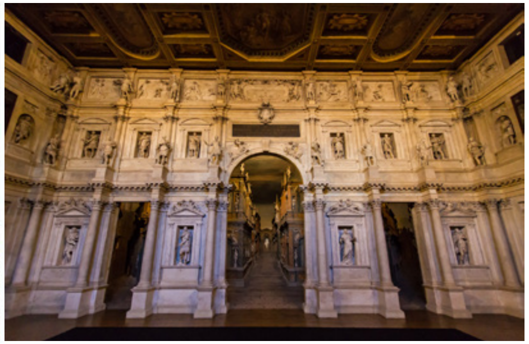


Figure 1.2: Set design in the Olympic Theater of Vicenza, by Palladio, XVI century

Figure 1.3: Set design by Robert Wilson

the massification of LED lighting and its versatility (due to the great range of different shapes and applications, and excited by the energy efficiency). Similarly, theater is slowly taking in the use of LED fixtures for more than secondary purposes, in a recent past being predominantly thought for architectural purposes to reduce the energy consumption. It is not unusual to find several renowned architectural lighting designers with a background from theater, and therefore a very clear influence in contemporary architecture of the stage realm. Arguably, the wide range of colours and contrast used to describe different situations and trigger different moods found on top of a stage can be (and is) very applicable and beneficial to the architectural world. On the other hand, the late adaptability of lighting fixtures to a particular geometry used in architecture can very well be explored in performance, which generally uses very little light integrated in the set itself, generally coming from an "external" grid system.

As stated, one can already see these two worlds merging in art installations (figure 1.4, 1.5 & 1.6), public spaces (figures 1.7, 1.8, 1.9 &1.10) and lighting festivals like the traditional Fete de Lumieres in Lyon or the more recent Sydney light Festival. This proliferations of a more artistic approach in the public

Figure 1.4: Light installation by James Turell

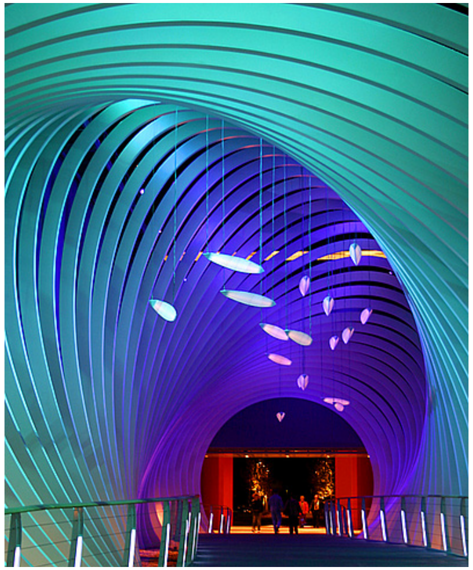


Figure 1.7: Nova Eventis in Leipzig by Scenario Licht

Figure 1.8: Kingston Bridge in Glasgow, by Martin Professional lighting

Figure 1.5 & 1.6: Rooms of light, by Dan Flavin

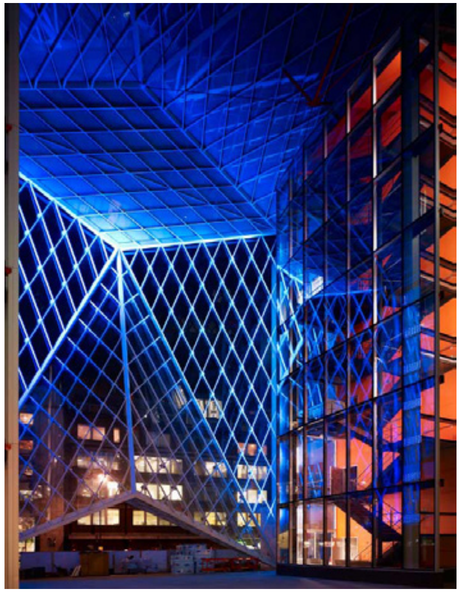


Figure 1.9: 55 Baker street, London, by Jason Bruges Studio

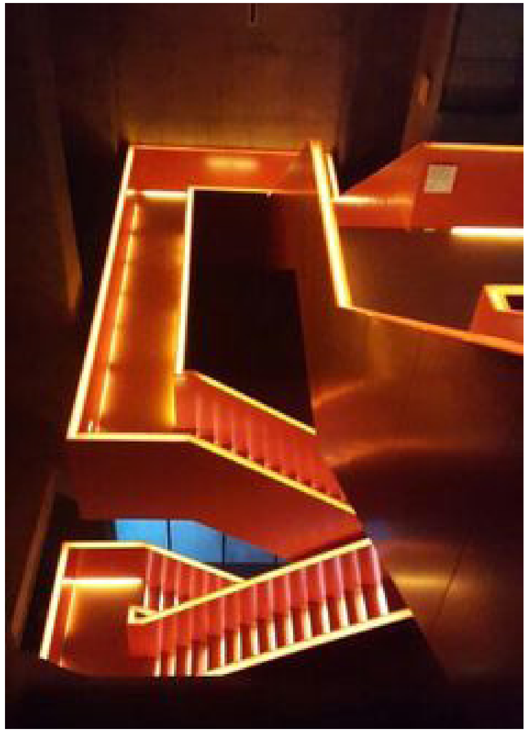


Figure 1.10: Zolverein Coal Washer by Licht Kunst Licht

realm sets the starting point towards a similar conceptual value in interior spaces, still underdeveloped in terms of a more dynamic approach (aspect in which this paper will concentrate towards).

In some of these more conceptually charged light spaces, the artist or designer brings a whole new meaning to the environment, seen specially when applied to interiors, bringing the light molded atmosphere to a user scale; the viewer is not a mere spectator anymore, but becomes the main actor of a reshaped, altered space.

Arnold Chan, one of the world's leading architectural lighting designers and founder of Isometrix lighting explains: "You need the theatrical architectural expertise to fulfil the creative side of things. (...) in the early stages what we are doing is creating an instrument of light, and then at the end we can play it in different ways. This is particularly true in homes or hospitality environments, where there's the need to create different ambiences at different times of day. (...) But you also need to understand the architecture, (...) to be able to perceive in three dimensions".(3)

As an approach to the scene creation and a way to establish some criteria, this paper deepens into the technical progresses in both realms, with colour as the main exploration trigger. Subsequently, the differences in technologies in both worlds and why LED, a dominant technology already in architecture, is just starting to make its way in theatre, and how, the other way around, the newly LED technology developed for theatre can be an interesting consideration for architectural and urban spaces. It will also investigate how scene creation is not only a subject to fiction, but also to architecture, and how can this be achieved with light.

Ultimately, this research is also aimed at creating more innovative solutions in architecture, with a bigger focus on the user experience and perception than the standardized regulations. Alternatively, to create more energy wise solutions in theater without compromising creativity, again, based on the user experience.

2. Characteristics in theater and architecture lighting

To be able to compare both worlds and see how can they/do they influence each other, it is necessary to evaluate what are the different main lighting purposes in both.

What defines lighting in theater?

<u>1. Flexibility</u>

It has to constantly adapt, to move, to create different focal points and highlight different elements as the play/dance goes on. Not only accompanying and supporting, but telling the story along with the actors. "The lighting conditions (of an environment) are recreated on stage and the audience associates the stage with the actual environment relevant to those lighting conditions". (2) Carpenter, page 72. Therefore, it is constantly changing.

<u>2. Codependent on one unique point of view</u>

It is always constructed having the public's location in mind. This gives the necessity of creating layers to simulate depth. It also becomes character based; as the most important thing to see is the action of the actor/dancers, there will always be lights specially aimed at the facial and body aspects. "The selective visibility (...) or making the performer visible is the most obvious function of

Figure 1.11: Reigen play, Brussels, 1993

Figure 1.12: Tankred Dorst, directed by Jens Daniel Herzog, 1997

stage lighting. The ability to direct the audience attention to the most important characters or action is very useful in a production." Carpenter, page 74 (2). This fact, consequently, divides the space into action and background.

3. Invisible/not present source:

In general, light sources are rigged above the stage and not visible to the viewer. "although some productions make a feature of the lighting equipment by hanging it in full view, the majority still prefer concealment." Bentham, (1).

Figure 1.13: Bigre, directed by Pierre Guillois

Figure 1.14: Robert Wilson stage design

4. It is an unveiling process

A good lighting design in theater creates contrast not only amongst the same scene, but between scenes. Especially in lower budget productions, it is very noticeable how rooms, walls and architectural elements in general are often suggested/ build with the power of light. In figure 1.13, for example, in the same scene 3 different rooms are created thanks to three different lighting setups. "A setting on stage need not be a familiar and natural affair. Just as the audience can make an association with a familiar lighting context so they can 'see' an abstract or non-natural setting through unfamiliar lighting conditions. Carpenter, page 74 (2).

5. It uses colour as means of expression

To highlight elements depending on their own characteristics, to create moods, to evoke a response from the viewer and to indicate transition of time, action, etc (figure 1.14) .

6. The power of darkness

In theater, everything that is not lit does not represent an empty space, but works creating an undefined continuity that the mind fills automatically. Also, because it is a closed environment, it doesn't have to compete with daylight: "as the theater's house lights fade, the audience adapts to lower levels of intensity".Carpenter, page 74 (2).

What defines light in interior architecture?

1. Integrated in the construction process or in the form of light objects

Especially in the case of interior architecture, to create a horizontal wash, generally downlights have to be planned at the time that the interior is constructed. Similarly so in exterior architecture, with the possible exception of facade lighting. This generally reduces the possibilities of flexibility within changing or adapting the wash in architecture to a dim dependent on presence. Light "objects" (such as table lights, pendant lights and floor lamps) are placed dependently or independently of the construction process (mostly dependently in public hospitality spaces, generally independently in private houses). "When architects design with light, they often conceal it it within the structure or furniture of a space - in recesses, in coves, or above and below fitted elements." Chan (3).

2. Multi focal point of view.

Lighting has to respond to the constant mobility of the users around the room, and to a variable number of people too.

3. Practicality

As a livable space, lighting in architecture has to respond to different needs. A lighting designer has to constantly have to have this needs in mind and try to fulfil regulation at the same time.

4. Geometry based: related to the integration

Generally a good lighting design responds and depends on the shape of the architecture and the space. “Light a ceiling and you raise the roof; light the walls and you push back the boundaries. Position individual lights around a room at different heights, or delineate pathways at low level, and you invite exploration. “Another type of spatial description occurs when lighting is used to accentuate form or to bring our textural contrast and material character. Graze light across painted brickwork and you reveal the tactile qualities of the surface where shadows fall in the fips, hollows and ridges. Sidelight a vase and you emphasize its contours.” Chan (3).

3. Hypothesis

The final hypothesis of this thesis is: architecture, as in theater, can be considered in terms of background and action based, which gives certain allowances. The main action is human centered based (as it is actor based in theater) and characteristics like the colour of the skin and the fidelity in the tones of the objects around should be the most relevant, which means that all colours of all the objects should be rendered in its best quality for the human eye. It wasn’t long ago before it was widely known that LED still didn’t not achieve this; today there are a wide arrange of very high quality LED’s that probably the common user would have trouble identifying from a tungsten.
However, “secondary objects” that surround the main action/actions, or the background, have the advantage of a wider flexibility of being in different colours or whites with different chromaticities, and apply them according to different surfaces depending on their characteristics. The role of colour will have then an important weight in this paper, as a tool used in theater that can be used in interior architecture to redefine and ultimately delight. There are a variety of interior spaces in which different kinds of activities and levels of interactions happen within, and lighting has the potential to respond to that. In this case is where LED still holds its maximum power and does not necessarily create a dissonance if used with tungsten.
The aspect in which performance and architecture really differ is, one is made “to be seen”, and the other one “to be lived”, but in any case both of them are human centered, and so should be the light that defines them.

Two tests will made to explore this scope. Each of the tests will have a sub-hypothesis and consequently a sub-conclusion, that will together lead to one final conclusion. Both of the tests wil be hightly based on perception, “The difference of vision and perception, (...)the dinstiction between providing lighting to make things visible and providing it to influence the appeareance of everything that is visible.” Cuttle, (25).
The first test will, through an inside in theater lighting, explore the performance of LED to deliver different colours, and answer the question of why theater still has not immerse itself in the world of light emitting diodes like architecture has. Furthermore, conclusions in this aspect will hopefully shine some light in the use of colour in architecture technologically wise.
The second test will apply coloured light into a virtual space, exploring through distribution the possibility of treating an interior like a theater play.
In summary, through literature and two tests the role of LED (efficient lighting) in theater and the role of colours (scene making) in architecture will be explored, with a crossing solution for lighting applications between the two.

How can the flexibility in scene creation and colour criteria in theater benefit the perception of an interior architecture space, and how can the latest improvements in efficient lighting in architecture benefit theater?

INTERVIEW TO PROFFESIONALS IN THE INDUSTRY

1. Lighting design for performance

Joseph Mercurio, freelance lighting designer and coordinator for performance technology at the VCA in University of Melbourne, answers to some questions about theatrical lighting and LED in performance. He is also the designer of the Grant Street theater in the Univeristy of Melbourne, one of the first theaters in the world that has fully incorporated LED.

Why did you get into lighting and what do you like about it?

By manipulating light you get very involved in a, sometimes obvious, sometimes subliminal level.
My lighting fascination is within the negative space more so than the positive space. In a lot of my lighting designs i try to explore and expand it, to highlight the contrast within the positive space. Discrete darkness to counterpoint the brightness, (what am i showing partially but also what am i not showing).

I highlighting the darkness, so darkness becomes a very important part of the narrative of light. We often focus on what we light (what we see), on how we sculpt and how we shape, but darkness in its graduation, from absolute darkness to different shade levels, really can help tell a story. You can motivate an audience through selective focus.
Everything (in lighting) is about contrast. Its only bright because over there is dark.

How do you use light to establish a context in theater?

I've had a number of shows where i have had the joy of being able to create that structure within a lighting aspect (beams of light through haze, walls of light etc). Once again, a lit space versus a dark space vs a lit space so that you carve up the space. And there is something special about having a beam of light 30m away just shining through to arrive at a point; not only do you light the point beautifully, but because it has defined the space through its journey; and so suddenly, we are not just looking at a close up view on a camera or just a spotlight on someone, we actually looking at the distance (the light) took to get there. As an example, what we've created is an analogy to the vastness of space, because light has come so far to arrive at that point. It is not just (the actor) that we see, it is the journey it took to get to that point.
So its the power of light to metaphorically represent a bigger, different space.

What aspects of theater lighting do you reckon would be important to explore in real life, in architectural?

It's challenging; Theatrical lighting by its nature has to cover a broad range of scenarios in one installation, while architectural lighting you are lighting for one application only. Say, if you are lighting a lounge room or a factory floor, there is a narrow range of activities going on. If you are lighting a theater show you may be lighting that very same location on stage to be night, to be morning, to be a surrealistic impression of the memory, so you have to have a lot more variation within a small space, where other scenarios have a very limited activity taking place. We work very similarly with cues: so at this particular cue i may start with an ambient level, so that i know what my other characters are doing, an unimportant action or the scenery, basically those things that are visually interesting but not important, and then I focus in the area where i need to be much more specific, and I build that so it sits on top or mixed in with the ambient.

The other way around is focusing on the moment that I need to highlight, so I build that moment, and then I look around and ask "now what do i want to blend". So thats the two ways, starting with that key point, or the ambient fill. Both architectural lighting and theater lighting work on that.

Its interesting otherwise the fascination that architectural lighting people hold with theater lighting design, and i think that has a lot to do with colour. Predominantly we are all chasing the same balance of ambient, key to task lighting. We use a lot of colour, while commercial and architectural lighting don't use colour.

A lot of people in those roles don't come from an artistic background, they come from an engineering background; they come from a very logical, numbers, control of specification place, they have not come from a place of mood, desire, impression. This is how you design, you come in with the question: what is my intent, what am i trying to achieve.

About the Grant Street Theater, what motivated you to build this system away from tungsten?

Its about being environmentally responsible. Some people told me that the use of LED would "limit their creativity". I get the attitude that (theater) is separate from that (irresponsible consumption).

When I had the opportunity to change the Grant Street Theater, I felt that the best thing I could do was attack my area first. So by leading the charge and getting the LED equipment so we have a long life low maintenance. and low cost solution, then we can inform other departments; so that we can create a database for anyone who needs it. Basically use our technology and artistry in a less destructive way.

It is only very recently that we've had reliable colour consistency and to have a good broad spectrum white out of the LED; still not perfect broad spectrum but we got closest to that.
Again, it does come down to contrast; if (for example) you ban all tungsten, all incandescent light sources, (already) from the moment you walk into the foyer (of the theater), you start training the eye to a different acceptance of white light. So to achieve the goal, it needs that bold step of exclusivity, so that the eye immediately starts to accept and calibrate a new white.

Whats the transition, how can theater start applying this, being really costly? A starting point?

A small company would do really well by selling they (tungsten) gear now and invest it in LED, are therefore reducing all of their running, cabling, air conditioning costs. It is still money, but the financial argument is based in the long game. It is true that a lot of people dont have money for the long game, it wold be good if theaters started getting goverment support by buying equipment, starting to push towards a renewal and in return wanting to see a percentage of that of enironmentally friendly and low power.
Small companies can start by changing the back light, then the side lights and so on (as an LED system), of course you want to buy an entire system of one hit so they match colour and intensity.

2. Lighting design for interior architecture

Nathan Thompson, architectural lighting designer with a background of stage lighting and lighting manufacturing, founder and design director of The Flaming Beacon in Melbourne, Australia, will be answering questions about colour and design criteria.

What's the criteria to create this scenes in hotels? What are we trying to achieve, what is the user looking when they are inhabiting the space? There is a lot of theatrics in public spaces, but what about interior?

It is about balance of lighting; I like to think that what we do is a "brightness arrangement", I think that is what lighting designers in architecture and theater do; the visual composition, by deciding which bit is going to be bright and which one is going to be dark, in its simplest way. In order to do so, we have to do all these difficult technical stuff with mirrors, and spotlights, and bits of white paint and sometimes black wrap around a light fixture etc.

What are we trying to achieve with this?

What we are trying is to evoke a particular psychological response in our clients. In the case of hotels, we are trying to satisfy them in making "their clients" happy. I think normally they go to a hotel when they are looking for somewhere to sleep that gives them a particular feeling that is about escapism and comfort. So I would argue that we make this in the same way that a theater person to evoke this emotional response, to make them feel calm, maybe a bit challenged, or that the place that they are in is unreal, disconnected from reality, you don't have to worry about things in you day to day life. So these are the concerns when we are setting the presets: what are the people gonna think when they go in? That's what *the scene is. That's how we choose the levels. The only reason that we put the lights in the plan is so that we can set those levels, push the levels up and down to cause that calmed "sigh". And in the theater, these decisions come from the narrative.*

It has been observed than in some cases a way of designing an interior is to scheme out where people are going to look at first. Is that a way of designing for you, establishing a main focus in the room?

I don't think I would use the order in which the guest would look around the room at the motivation, but the dynamic sequence of their engagement with the space. Some formal arrangements require a very straightforward assessment of what's the primary focus, the secondary and tertiary maybe, but I'm not sure that's for the purpose of the order of viewing but for setting up a hierarchy in the composition.

In theater, colour use in lighting is predominant. How is colour currently use in interior architecture, what's the relationship with it? How often do we use it in a professional level?

Sometimes when we see coloured light in architecture it looks like a cliché version of what we think theatrical lighting is, as opposed to something natural. When we go to the theatre or a music gig, there is no reason for the viewer to think that anything should look natural. But to use colours in an architectural space that are not in the black body locus, there has to be a very clear reason of why are you doing it. It has to be handled very delicately and carefully, and then it can be sensible; if there is a reason in the lighting criteria of the space, the usually you can find a connection as a viewer.

Do you ever use it? Which case?

One of the circumstances in architecture where colour doesn't look bad its when its referring to nature. In this project we did in Sydney, the Rockpool (figure 2.1)*, a building built probably around 1880 with full height windows; we put some fluorescents behind those with a very dark blue purple filter, making a nice background against which warm white looks beautiful. Because it kind of refers to night sky, it locks in into everyone's understanding of how space should be. Even just simple things like playing with a very cool white and a very warm white, placing them against each other can be enough contrast in the right hands.*

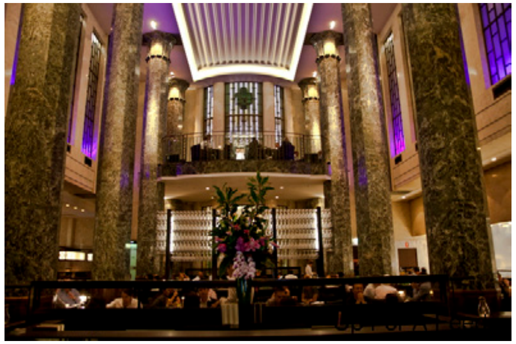


Figure 2.1: Rockpool in Sydney

What percentage approximately do you use of LED in a whole project?

We are still using a lot of full spectrum halogen lighting because of the particular niche that we work on (hotels).It can be argued that it is not bad energy use to still employ halogens for the quality of the light. Warm light produced by incandescence has had no parallel until very recently. It's getting very good now, some phosphor arrangements like Xicato or Lumenetix are getting so good that is very difficult to argue anymore that there is a place for halogen rather than its controllability, and even now it's a bit of a dead argument. So the main reason is cost now.

What would you still use halogens for?

The position that we use is LED (and prior to that fluorescent) light in the places where there is not the primary place for illuminating people: wallwashing, uplighting, background stuff; and then, sprinkled amongst it, a bit very high quality incandescent light, around a table, sofa, etc. So that the primary quantity of light is established by the high efficiency and then the local light, where the real interchange of people takes place and they are looking into each other's eyes, is were the good light is.

There has been a recent trend of making the user more active in the lighting design by making flexible lighting arrangements. What's your opinion about it?

It makes trouble for us, means that they want to keep all their options open. Makes brightness arrangements difficult unless we use spotlights that can be moved around. A lot of times it just implies that the client will have to move a lot of things around. With precision, a lighting designer can actually control the environment better. Normally we have to forgo the precision in order to provide the versatility.

03

COLOR SPECTRUM TEST

1. Introduction & Discussion

LED in theatre: a slow evolution from tungsten

While working as a lighting assistant at the National Theater in Nice (France) and being able to help hosting almost twenty different plays from different companies coming from several places across the world, one thing became clear: LED was very rarely used, and all the fixtures employed by every single company were still based in tungsten. The most basic consequences of this attachment to tungsten are, to name a few, the high wattage employed by each fixture (an average of 1000 W each), which leads to very temperatures reached by the body, which leads to the constant need of replacing colour filters, which deteriorate quite fast, and of course implies the use of a fixture per colour, incrementing the number of fixtures used, as well as the subsequent transmittance loss given by the use of any filter. “The problem of filter burn-out is aggravated by heat from the lamp. Because the filament generates light by becoming ‘white hot’, the lantern housing and colour filter also heat up.” Bentham (1). High wattage usage demands not only a huge energy use in big theatres, but a need to employ a very powerful and numerous dimmer system. All these reasons help in questioning the reason why, with the existence of such a low power and self colour changing technology like LED, theatres continue to endorse tungsten.

One can notice the major presence of LED in public architectural installations with a satisfying result; a whole range of colours and effects are displayed with a very significant reduction in watts. Same in concert lighting, where LED and its fast colour changing possibilities benefit endlessly the dynamics of a musical event. The major question raises:

Why is theater still so far behind in the use of LED?

It is not only a matter of money (changing a whole lighting system is very expensive and not every theatre counts with that possibility), but also a matter of achieving whites and colour quality. Arguably, these are more important in theater than any other artistic medium because it is another means of expression: it has to highlight the action precisely and, as said before, accompany the actor, integrate them with the rest of the space consequently, with no difference in hues when the same colour is used. It has to be trusted not to cause irreverent/ repeated shadows when not desired. In other words, what lighting designers want when using LED is tungsten quality (even more so in theater than any other realm).

New LED technology tries to address this desire, this recognition of the tungsten as the best technology possible in terms of colour. However, the following questions rase:
What is tungsten best for exactly?
“Up until the tungsten halogen lamp, every form of light from the caveman forward has been generated by heat. We have a very subliminal, primal relationship with light. LEDs produce light by passing electrical energy through a carefully mixed chemical compound. The wavelength produced is very narrow and not full spectrum like tungsten. And yes, visually there are differences — color rendering is not good, they don’t make skin tones look good — but also I think we need to consider the subliminal response to this artificial light. Development of the LED, or “artificial” light, creates a discord within our human growth. The eye is used to seeing things in warm tones, as if produced by fire. When that convention shifts, so does the human response.” Holder (1) .
Basically, what Holder is saying is about the natural light outputted by tungsten; that is, warm white light. The white light that tungsten delivers makes things look so natural and good that is precisely the base for all LED white light comparison: the CRI measurement.
The measurement of CRI has its comparison value set on a black body radiator (and that is precisely what tungsten is); However, studies show that CRI, which high index is almost always shown when purchasing LED as a quality measurement, is not a good guide for analysing LED. Developed to show the colour quality of fluorescents and HID, LED wavelengths that dont sit exactly under the curve of a tungsten in the determined colour palette stablished by CRI score poorly, while probably rendering colour satisfactorily. (5)(Figure 3.2) Other studies show, however, that “the (CRI) method has some limita-

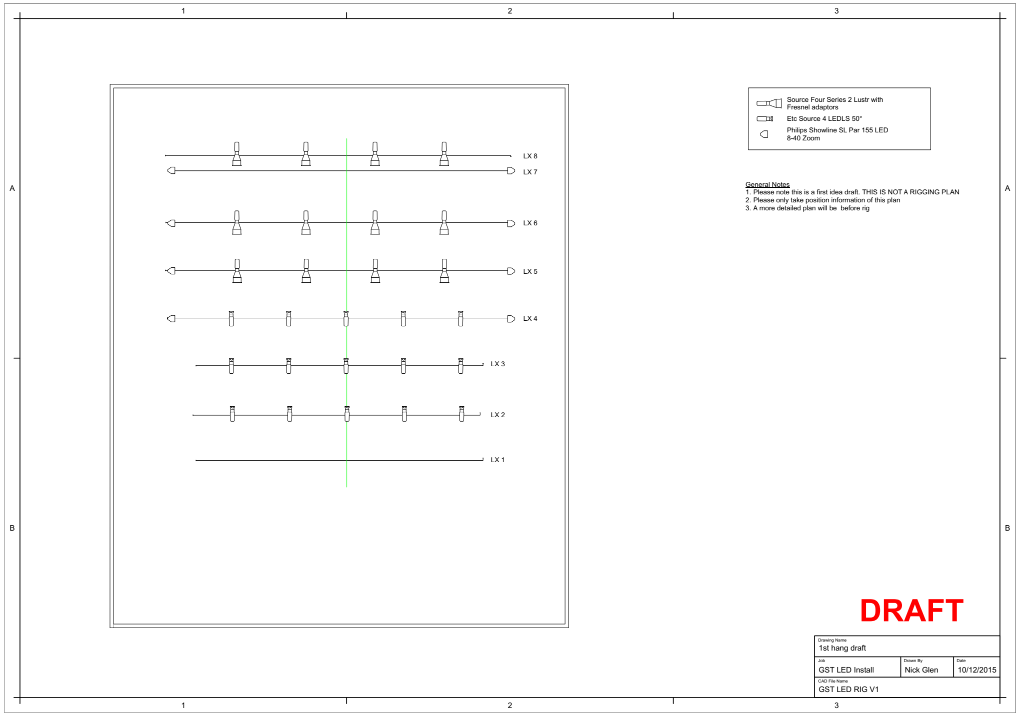


Figure 3.1: Grant Street Theater lightin g plan

tions, but is a reasonable indication of the performance of various light sources. It used to be considered that an average colour rendering was acceptable for normal environments and higher colour rendering was only required in areas where specific colour rendering was required. In recent times it has been shown that although relatively high colour rendering may not be required for the specific task being performed, the visual environment and level of user satisfaction is significantly improved with higher colour rendering sources. This is probably due to the better rendering of skin tones and the general increase in colourfulness of the space." Mclean, page 8 (6).

How about monochromatic colours? Can it be established that colours are also better when performed by the tungsten plus filter combination? We know that the colours of the LED may differ from the ones performed by tungsten fixtures, but to what extend does that matter? While it is known the immense extension and palettes that colour filters offer, it is not to be forgotten that a filter is, after all, a pigmented material that works "taking wavelengths away", whereas colour in LED happens directly mixing coloured chip sources. LED manufacturers promise millions of colours just with RGB mixing, but are they able to reproduce exactly the colours that the designer wants?
"White emitters generally produce a narrow spike of colour from their pump source, accompanied by a sloping hump of output in the green/yellow/orange range. In fixtures that use multiple colours of LEDs, the combined spectral output is generally a series of peaks and valleys across the spectrum. In all LED fixtures, the final output rarely reaches into the extreme red and violet ends of the visible spectrum. This has an important impact, especially in the deep-red region that so strongly affects the appearance of human skin tones, wood tones, and other organic materials. It is difficult and very costly in terms of efficacy to include large amounts of the long-wavelength red light that flows so richly from all tungsten sources. This hit to efficacy will always be there; it is a fundamental component of the way we quantify visible light." Gerlach (7)

In an aim to understand how close or how far is LED to get into the theater use (in a more particular way) and therefore into the colour quality competition (which,in a broader way can be extended towards architectural conclusions) , the test that follows examines precisely what is LED best for and capable of in terms of colour, and ultimately, how much do these differences matter. The CRI will be considered briefly for analysis, but the test will take a step back and establish relations between perception of colour (in the eyes of the beholder) and spectral data from the light sources and reflected from the colour of the skin, ever so significant. While it is true that other colour fidelity measurements have been or are being developed (like TM-30 that amongst other improvements measures 99 colours instead of just 15) (8), the Esensetek SPD app, like most of the manufacturers, displays CRI only.

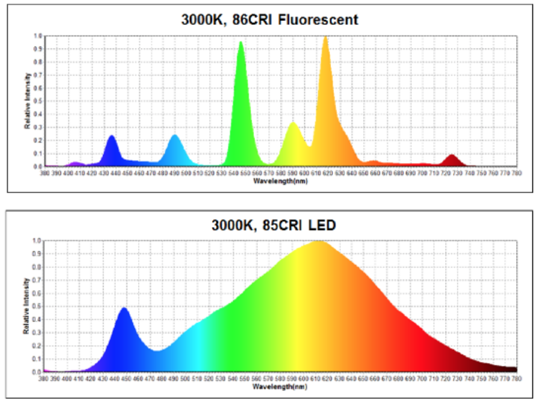


Figure 3.2: Graph comparison between an LED and a fluorescent with the same CRI, showing that the fact that they have the same CRI does not necesarily mean colour quality

For this purpose, this test will not only put in the table a profession-

al theater RGBW, but also the latest LED colour technology that adds 4 more colour chips to the regular red green and blue. This fixture is provided by the ETC company, the Source 4 ETC profile. Of course, the eternal tungsten will be assessed to as the standard of the comparison.
The hypothesis of these comparisons is that there is no white like the tungsten, being able to show to the spectator colours of objects that are slightly missed with an LED. Furthermore, that the reason why theater designers and some interior architects are still reluctant to use LED (beyond the budget reasons) is because at the time of focusing the attention on an actor or person, tungsten ability to represent skin colours is unbeatable, and this is an unforgiving factor as all the action and center of attention is performed by human beings. "Various studies indicated that in almost every lighting installation, either consciously or subconsciously, human complexion is a very important criterion by which the installation is evaluated." (9) In terms of the test, that the curves in the spectrum in the LED have to be almost identical to that one in the tungsten (with pretty much no spikes) to be able to compare.
Similarly, on monochromatic colours, while there will be a difference, it won't be so palpable between tungsten and LED, not even when an RGB LED is employed. That spikes in the spectrum in this case won´t matter that much as long as they peak exactly where the colour needed.

In conclusion, that the combination of tungsten for whites/frontal lights plus LED for colours/background/side lights is a legitimate intermediate step towards a full LED change, until the budget is available or until an LED can fully substitute a tungsten white quality wise (in the case that it does not already meat tungsten colour
quality standards).

"The conflict of efficacy and rich spectral content is one reason that many designers have preferred a hybrid tactic with solid-state lighting, combining both tungsten and LEDs in a stage rig. LED luminaires provide a strong punch of colour, while conventional tungsten units boost brightness in white and fill in the critical long-wavelength parts of the spectrum." Gerlach (7).

The test will be performed in the Grant Street Theater in Melbourne, Victoria (Australia). This venue has as front lights the ETC Source 4, and as side lights the Philips Showline SL PAR LED (figure 3.1). This decision of selecting a LED as front of house seems bold at first. However, the ETC website reads:

"LEDs aren't just for scenery anymore. The Source Four LED Series 2 luminaire is so bright, so adaptable that it can go anywhere in an installation, even front of house. With its advanced mix of LED emitters, it can beautifully illuminate the talent, allowing easy adjustments." (11)
Not only ETC assures it, but Rob Gerlach, founder of Selador and therefore the system of the 7 colour chip, says about the ETC Source 4: "RGB is more than sufficient for many applications; however, some uses require far more spectral components. Many of ETC's products happen to use seven colours of LEDs, because this approach gives the fixtures a much broader gamut of saturated colour as well as white light and soft pastels that much more closely mimic the spectral content of tungsten, with and without gels. This seven-colour system also combines the various emitters in very specific ratios, because not all colours of LEDs are of comparable brightness. Very few LED luminaires take this approach to colour mixing. Additive colour mixing is an entirely different way of thinking than the subtractive method used with filters on tungsten, and it can be rather non-intuitive, especially when dealing with more than three primary colours. It takes a very good control system – one that knows the specific colour capabilities of a given LED fixture – to make the job of additive mixing quick and simple. Thankfully, ETC and other console manufacturers are wise to this requirement and are continually improving their colour-management options in their desks." (Figure 3.3)

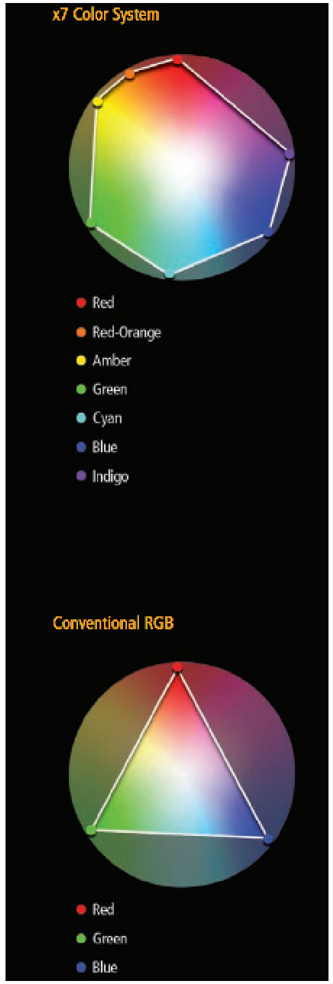


Figure 3.3: Difference in gamut between an RGB LED and a x7 Color LED thanks to the addition of 4 more colour chips

The Grant Street theater in Melbourne, following the steps of the Californian theater Sunnyvale is a perfect example of a tungsten to LED transition. In the following article, the reasons why such a drastic change has become worth it get revealed: "Despite the higher cost of the fixtures up front, Sunnyvale Theatre has calculated that installing only LED luminaires would save them a lot

of money over time. The theater didn't have to purchase two new transformers at a cost of $80,000, or pay electrical contractors to run more conduit and install more copper throughout the building. The venue no longer has to pay for lamp replacements, which cuts down on costs and waste going into landfills. The fixtures' reduced maintenance saves them $1,000 per year. Sunnyvale Theatre also reduced risk, because technicians aren't up on ladders doing weekly fixture maintenance. And the biggest savings comes from the reduced power it takes to run the LEDs. The theater has cut its energy expenditures by 80 percent - a total of $16,780 per year. They also garnered an award of excellence from their California Parks and Recreation Society district, which recognized the move to an all-LED rig as a 'best practice' for municipal venues. Since the installation, electric company PG&E has approved a wide variety of ETC LED fixtures on their rebate list to help offset costs when retrofitting traditional tungsten theatrical fixtures. "This is a landmark event, says Mike Wunder of Wunder Lighting and Controls, "because no theatrical fixture has ever been approved for a rebate and it's also the first color-changing LED to make the list." (12) It is clear that cost wise it is a more cost efficient change in the long run. However, the question of it really being a fair substitute for tungsten in terms of light quality, enough for designers and theaters to undergo the economical investment, will be assessed.
This paper is written with the collaboration of Joseph Mercurio, (interviewed previously in this paper) the promoter and lighting designer of this space, still one of the first fully equipped LED theatres in the world.
The first meeting with Joseph confirmed that the use of tungsten in performance is still majoritary. He stated that one of the problems a couple of years ago that LED had was that the colour changing range in the performance spectrum did not usually offer more than a 3 colour chip, (with the addition in occasions of a white chip , producing the RGB light source, to let the white light not be a result of poor colour mixing from the other RGB chips) which still, did not make an LED source comparable to tungsten in terms of colour change, tungsten having a huge spectrum of colour filters that offer endless possibilities of combinations and layers of lighting. (show with examples the limited color range in LED, number of LEE filters)

As explained, the Source 4 has 7 chips as opposed to the regular 3 colour chips (4 when a white chip is added) used in previous LED fixtures for theater and architecture. "Opening" the colour gamut adding more single colour chips makes it possible to trace more paths from one point to another in the CIE colour space, amplifying the possibility to reproduce a wider arrange of colours. It is all thanks to the x7 Colour System by Selador acquired by ETC (13) and therefore their approach to the LED market. "While conventional RGB illumination renders colored objects unnaturally red, green or blue, Selador's unique seven-color system gives natural color to people and objects, making the Selador Series the only LED luminaires capable of interacting seamlessly with your conventional light sources." (14)
The Source 4 builders promise "tungsten like qualities". What new technology does the Source 4 incorporate exactly?


Figure 3.4: tungsten profile Robert Juliat


Figure 3.5: Source 4 Series 2 Lustr

"The fixture produces only white-type light, which is adjustable from 2700 to 6500K. (...) ETC's x7 Color System™ combines a balanced recipe of up to seven colors to create evocative color mixes. The Source Four LED Series 2 Lustr array takes the idea even further, with the addition of a lime-green LED emitter. Lime green increases the luminaire lumen output in open white and lighter tints to make them brighter and livelier, better matching the color of a conventional Source Four fixture. The lime also enriches color-rendering by better marrying the red and blue ends of the color spectrum, for truer-to-life light that fills in the gaps that ordinary LEDs leave behind.
We also added more red to the x7 Color System in the Source Four LED Series 2 array. Working in unison with the lime-green emitter, the extra red means the luminaire can produce ambers, straws and pinks up to three hundred percent as bright as those from the original Source Four LED™. The deeper, richer color from the Source Four LED Series 2 Lustr array will evoke the strongest audience reaction to your sunset, moonlight and dramatic scenes."


Figure 3.6: Philips Showline LED PAR 155

2. Comparing between light sources

The test focuses on the comparison between a standard tungsten profile,(TIBO tungsten profile by Robert Juliat) (figure 3.4) the ETC Source 4 LED (figure 3.5) and an RGBW Philips Showline LED (figure 3.6) par can in the colour spectrum. Ultimately it is an analysis to see how does LED manage to output a similar light to the one delivered by a mix of tungsten and filter. For that matter, white plus 4 colours will be compared using: photographic evidence, SPD measurements and in the case of the whites, CRI and CCT calculations. These will be measured with the Asensetek Essence Spectrometer, that measures a range between 380 and 780 nanometers. -here The test further explores the relationship between the aspect of the photographs (as a representation of perceived colour) and the CRI and CCT in the case of white light measurements.

1. The photographic evidence will be shown to a sample of seven people to determine the colours that they register in the photographs, and then compare the results against the measured data to see how the intensity and amount of different wavelengths affect perceived colours. First, a Ishihara test will be shown to each participant to make sure that they are not colorblind. (figure 3.7). The participants will be asked their opinion on colour of both in the paper and the face. In the case of them identifying white, they will be given the option to add one more colour to the white to define the tonality of the white. In case of coloured light, they will be asked to identify a minimum of 3 and a maximum of 5 colours, in order to establish the details of the perception from one coloured light to the other. They will be asked to choose from the CRI and CQS test colour patches (for unsaturated and more saturated colour options to choose from) in each photograph (figure 3.8). For a more detailed colour perception study, the CIE colour space should be used; this study is however a basic approach to colour perception, a first impression. The patches selected more times will be the ones who will determine the colours that objects appear to people. While these patches are not extensive, it is hypothesized that their selection will lead towards general coloring perceived, which is the purpose for this test. The photographs will be shown in isolation and not compared to each other, for participants not to be biased by the colours shown in other photographs. The participants are 4 male between 30 and 33 years old, and 3 females between 29 and 32 years old.

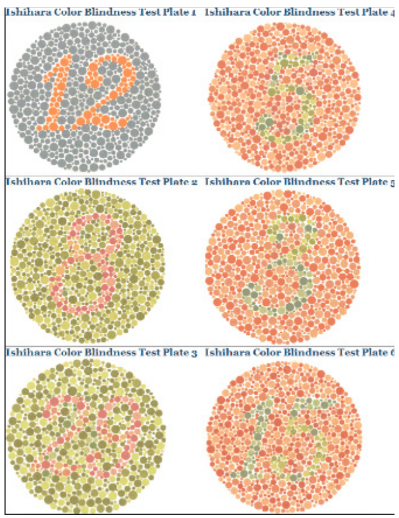


Figure 3.7: Ishihara Test for Colour Blindness

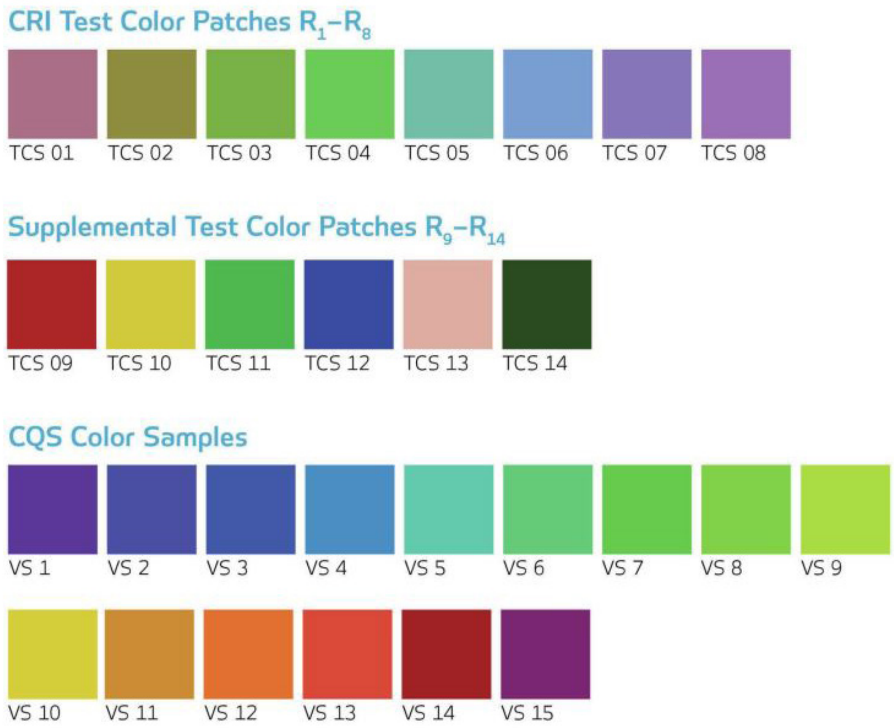
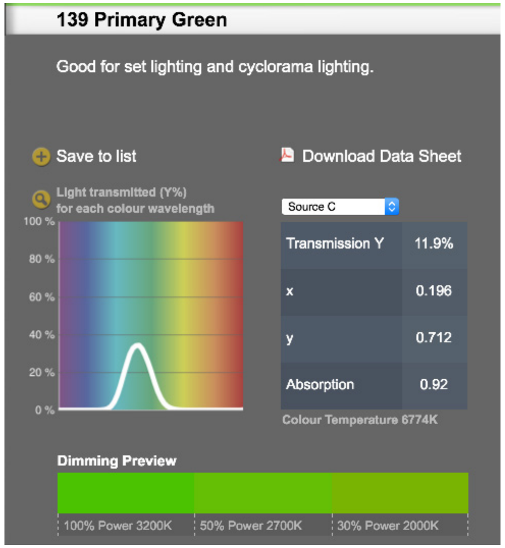
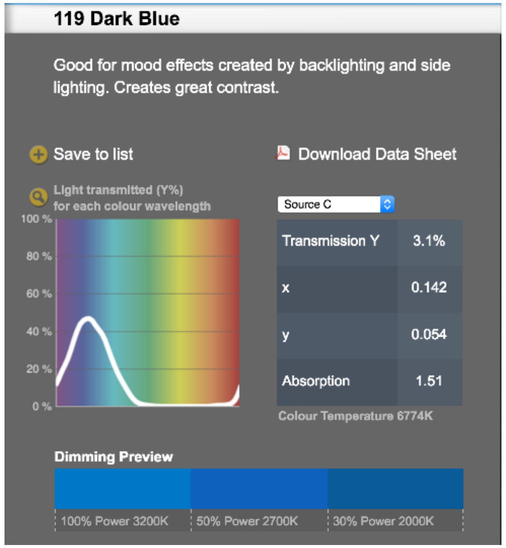
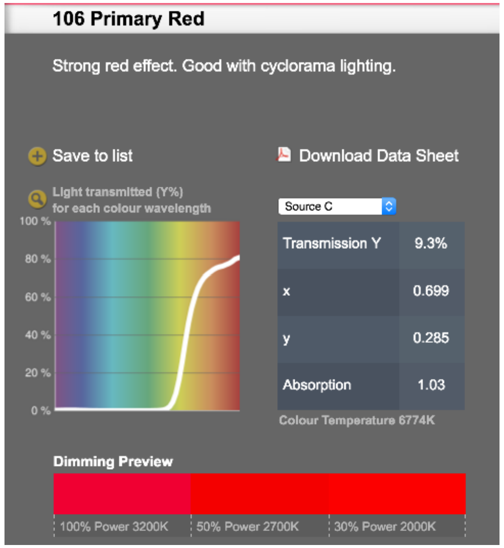


Figure 3.8: CRI and CQS colour samples shown to test participants

2. SPD: “Scaling each (SPD) chart to 100% relative energy allows side by side comparison of light sources with different lumen ratings (intensity) or wattages.” (15) The spectrometer used already measures SPD with a relative intensity from 0 to 100. This is important as the lights used to output very







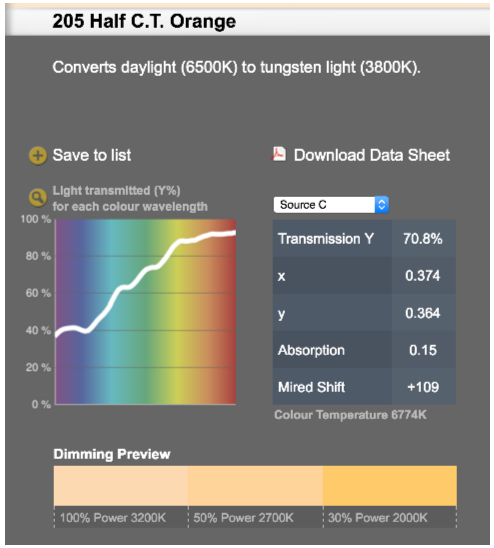


Figure 3.9: LEE 139 Green Data Sheet Filter

Figure 3.10 LEE 119 Dark Blue Data Sheet filter

Figure 3.11: LEE 106 Primary Red Data Sheet filter

Figure 3.12: LEE 204 Full CTO (Daylight to tungsten) data sheet

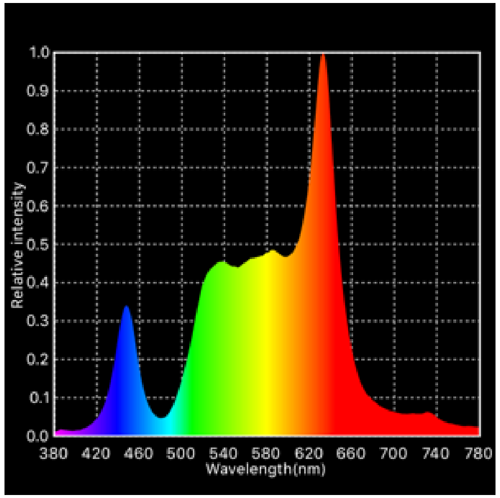


Figure 3.13: SPD measurement directly from the white Source 4 (tungsten preset)

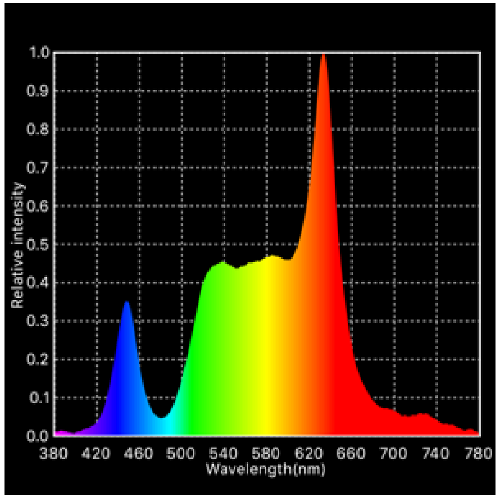


Figure 3.14: SPD measurement from the white sheet of paper in the Source 4

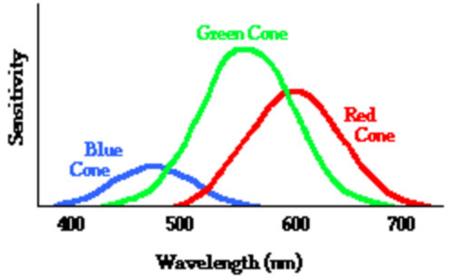


Figure 3.15: Sensitivity of the different cones in the retina responding to different monochromatic wavelenghts

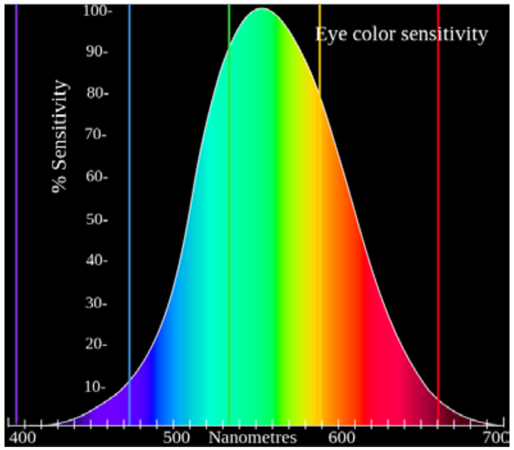


Figure 3.16: General eye colour sensitivity per wavelenght

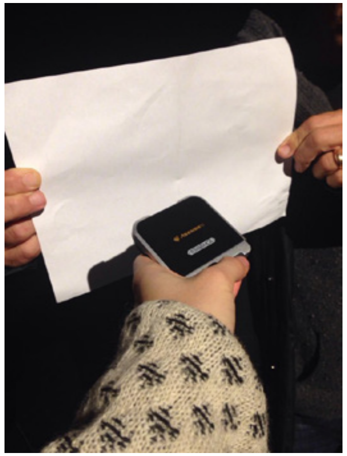


Figure 3.17: Measuring with the spectrometer from the white sheet of paper

different intensities that can't be paired: the tungsten is the most intense of them all and cannot be dimmed to less for testing purposes as the colour temperature in tungsten changes to warmer when dimmed. Another solution would have been calculating distance of the subject from the light source in order to equiparate the intensity received (doubling the distance decreases the light intensity to one-fourth of the original value.) (10) But as this is merely a colour comparison with relative brightness, the only matter it influences is in photographies, which will be assessed in post edition adjusting the levels.

However, another relevant parameter is to be had in consideration: the photopic sensitivity of the human eye. Because we are always talking from a visual point of view, and the whole purpose is to know how the viewer perceives the colour differences, it is important to perform a parallel comparison to the visual sensitivity at the time of specifying why some colours in light look more similar to each others, and also to estimate why some determined curves may be more important than others at the time of comparing sources. "under normal lighting conditions (photopic view), the eye is most sensitive to a yellowish-green color". (16) (Figures 3.15 & 3.16) Even though the test is made in a seemingly dark environment, the vision is still photopic: "Photopic vision relates to human vision at high ambient light levels (e.g. during daylight conditions) when vision is mediated by the cones. The photopic vision regime applies to luminance levels > 3 cd/m2." Schuber, page 275 (18) As seen in figure 3.30, the lowest footcandle level is 6.7 in the case of the Showline LED, which is 6.7 fc, equal to 72.1 cd/m2 in the SI system.

3. The CCT and the CRI will also be compared . It is considered that the CRI is not enough to understand fully the quality of the colour outputted by light: "Metrics attempt to characterize color mathematically (and may attempt to characterize the subjective experience). They tend to be imperfect, (for example, objects will looks different under sources with same CRI at different CCTs) but are still generally useful." Royer (19).
The reference in this case of the CRI is the black body radiator as the light sources are all below 4000 Kelvin: "The reference illuminant is taken to be the black body radiator which has the closest chromaticity coordinates to the test source, provided the test source has a CCT of 4000K or less." (20) (It is to be noted that although in the photograph of the measurement taken the patch R13 is more of a white colour,(Figures 3.18 & 3.19) R13 typically represents a light pale pink, close to the skin colour).

The procedure will be the following:
As stated, there will be three light sources compared. The two LED´s, the Source 4 and the Showline are currently employed in the Grant Street theater.(figure 3.1) The three light sources will be compared using the reflecting colours from a white sheet of paper for an accurate as possible information of all the spectra reflected by the light used (as white objects reflect all of the colours of the spectrum) (figure 3.17) and from the colours reflected from a model's skin, to address which one is better as a front light based on the colours that the skin reflects and to investigate the reasons why tungsten is difficult (or not) to substitute in theater. "The color of an object results from partial reflection of the spectrum emitted by the illuminating light source.If certain ranges are missing from this spectrum, the corresponding color components cannot be reflected or seen. If intensity is not uniform over the entire spectral range, color components with greater intensity are amplified, and

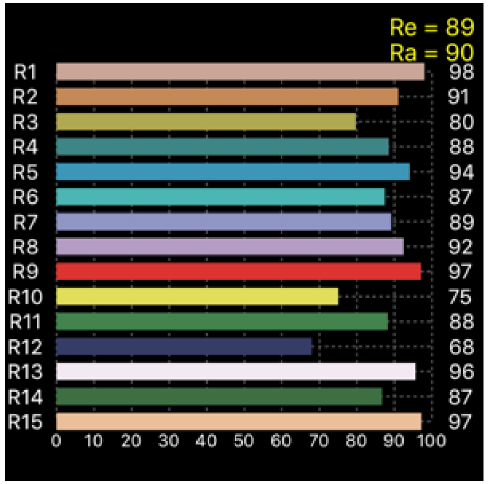


Figure 3.18: CRI per colour in the Source 4

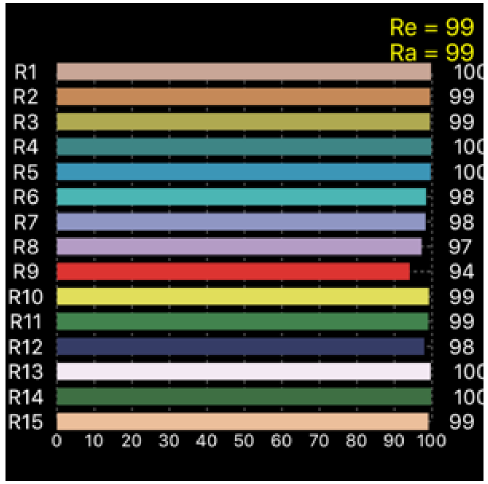


Figure 3.19: CRI per colour in the tungsten

those with lower intensity are attenuated.” (21) So in summary, when the spectrometer is pointed at an object (in this case the skin of the face), what we are looking at is wavelengths per reflectance. To make sure that the white sheet of paper reflects the wavelengths appropriately, a spectrum data set will be collected with the spectrometer pointing directly at the light source and then pointing at the white paper. As seen (Figures 3.13 & 3.14) the spectrum gathered is the same, also proving that the different SPD’s can be compared regardless of the intensity as long as they are measured against a relative intensity from 0.0 to 1.0.

The hypothesis is that while the spectrum will be very different, the visual output of the tungsten and the Source 4 will visually be very similar, as their spectrum peaks.

3. Test setup

1. The model is standing in all of the cases 3.50 meters away from the light sources, holding a white sheet of paper at approximately the height of the face, perpendicular to the floor and parallel to the light source. There is no other light in the room that may influence the result; the background is pitch black. The light sources are hung on poles above the subject, 3.50 meters in the case of both LED’s and 2.50 in the case of the tungsten, as it was situated in another performance space. It is hypothesised that while the difference in the angle of the light is slightly different, it does not influence in the actual spectral data collection. As said, the test will measure the spectrum of the reflected light from both the skin and the white surface.

2. All of the tests will be documented using the Essence spectrometer and a digital camera (Sony Nex 5N). This data will include the spectral power distribution. the CCT and the CRI. A photographic comparison of the shadows that each luminaire outputs will also be made.

3. The same colours will be measured in the three light sources: white, (tungsten white in the case of the Source 4), a red colour (LEE 106 red filter and its digital version (colour filter preset) outputted by the lighting board in the case of LED’s), a green colour (LEE 139 filter), a blue colour (LEE 119) and an amber colour corrector, very used for facial purposes (LEE 204) This filter is special because it isn’t a colour filter but a Colour Temperature Orange, designed to turn down the colour temperature of a light source to warmer tones. (Figures 3.9, 3.10, 3.11 & 3.12).

4. Before any sets of photographs are taken from any light source, the camera will be white balanced against a white sheet of paper every time the light source changes, to establish the colour temperature in the sensor and therefore to be able to take photographs as unbiased as possible. Ideally, all of the parameters of the camera when taking pictures would be equal (same opening, same shutter speed) but as the light sources have different intensities it requires a change in order to capture properly the colours and not be burnt or too dark. Instead, the histogram will be checked at the time of taking the picture to make sure that the whites and blacks are as inside the histogram for the achievement of a similar tonal range.

5. These data collections will be, at the same time, compared to each other in terms of spectra and CRI (on the whites). As the spectrometer just allows the comparison of two sources at the same time, The Source 4 and the Showline will be compared, as well as the Source 4 and the tungsten profile, in a sort of order from the least expected quality to the most expected one. All these comparisons will be made with a reference of 555 nm, the peak of photopic sensitivity, peak under which the photopic sensitivity curve will be displayed as a reference for the average colour brightness perception performed by the eye. Padfield (22).

6. There will be posterior level check arrange in Photoshop to make the photos as similar as possible in terms of brightness. All of the photos shown are already equalized allowing to a detailed comparison.

4. Results

*(figure 3.8 depicts the colours patches that are mentioned in this test)

A. **Trial of whites** (no filter in the tungsten, tungsten white preset in the Source 4, white preset in the Showline (no tungsten white option)

Figure 3.20: Model and paper under white tungsten preset S4

Figure 3.23: Model and paper under white preset Showline

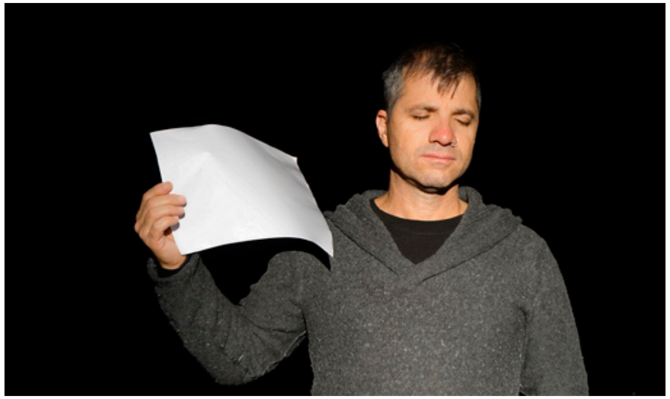


Figure 3.26: Model and paper under white tungsten light

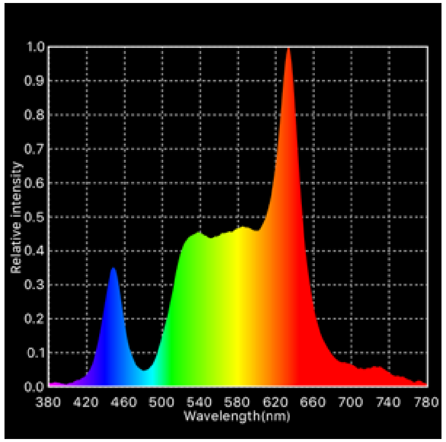


Figure 3.21: Reflected light SPD from paper in the S4

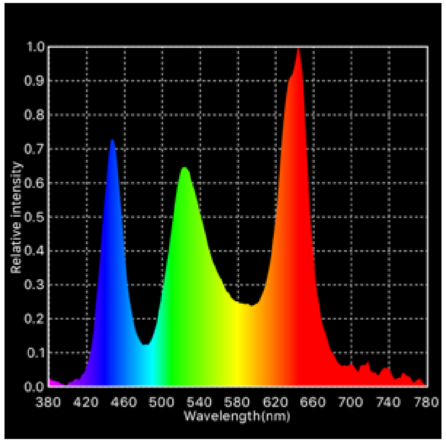


Figure 3.24: Reflected light SPD from paper in the Showline

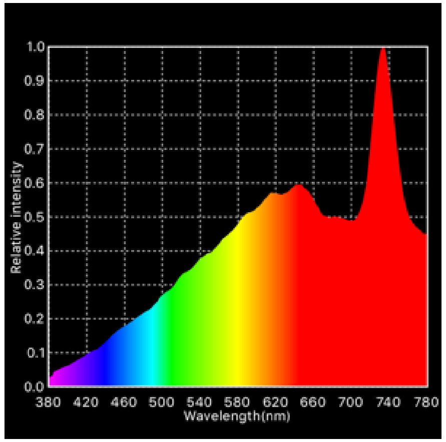


Figure 3.27: Reflected light SPD from paper in the tungsten

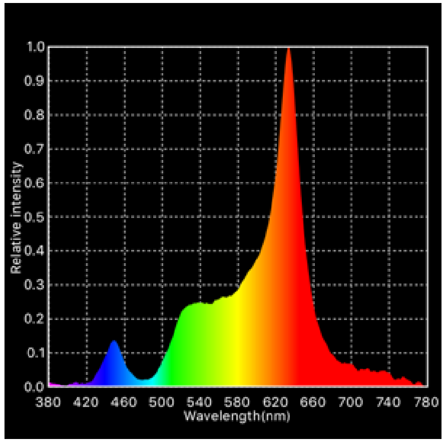


Figure 3.22: Reflected light SPD from skin in the S4

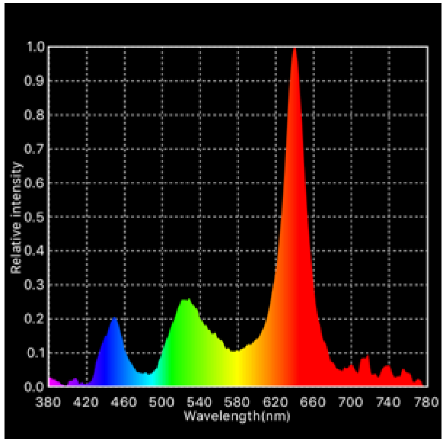


Figure 3.25: Reflected light SPD from skin in the Showline

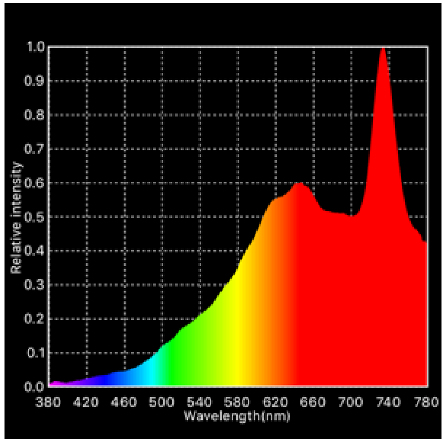


Figure 3.28: Reflected light SPD from skin in the tungsten

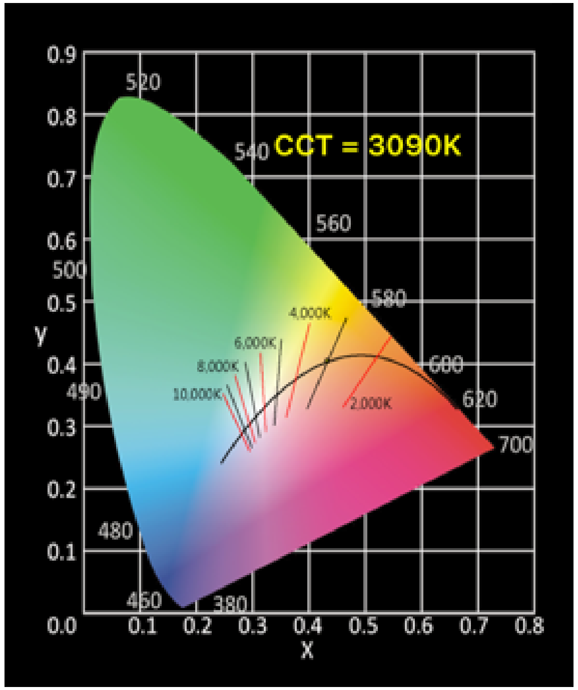


Figure 3.29 CCT in the Source 4

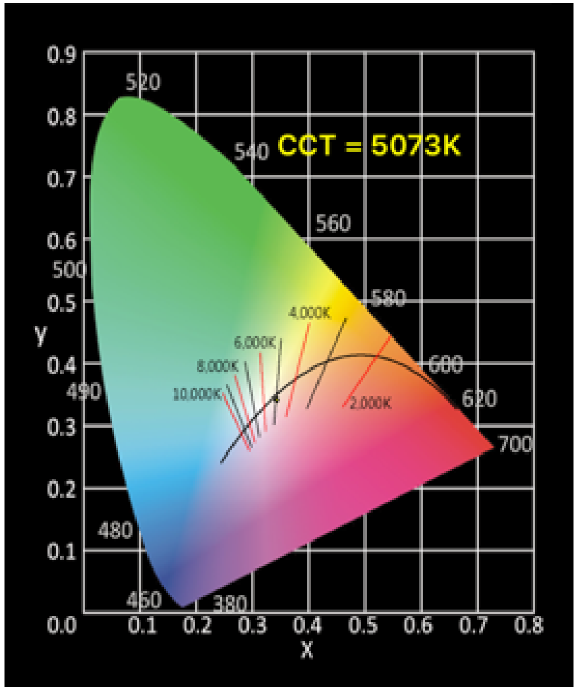


Figure 3.30: CCT in the Showline

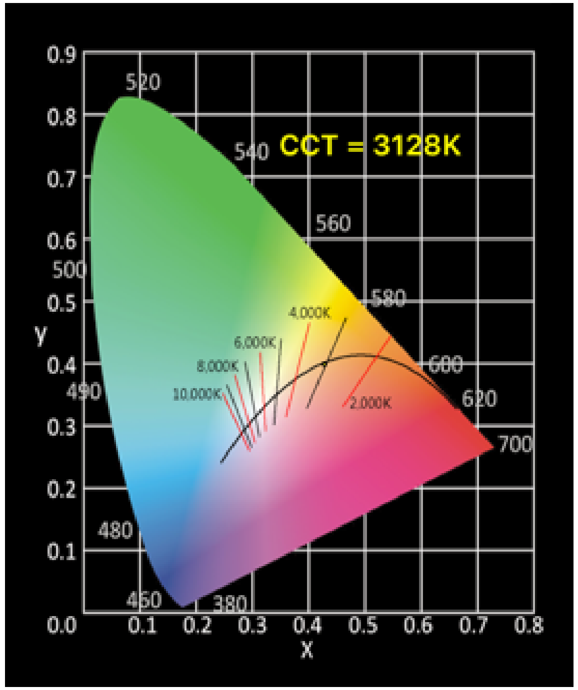


Figure 3.31: CCT in the tungsten

Parameter	Value
CCT	3090 K
CRI(Ra)	90
CQS	88
TLCI(Qa)	73.2
GAI	63.2
Illuminance	175 lux
Foot Candle	16.2 fc
λp	633 nm

Parameter	Value
CCT	5073 K
CRI(Ra)	68
CQS	83
TLCI(Qa)	55.8
GAI	118.9
Illuminance	73 lux
Foot Candle	6.7 fc
λp	644 nm

Parameter	Value
CCT	3128 K
CRI(Ra)	99
CQS	99
TLCI(Qa)	99.7
GAI	61.6
Illuminance	500 lux
Foot Candle	46.4 fc
λp	733 nm

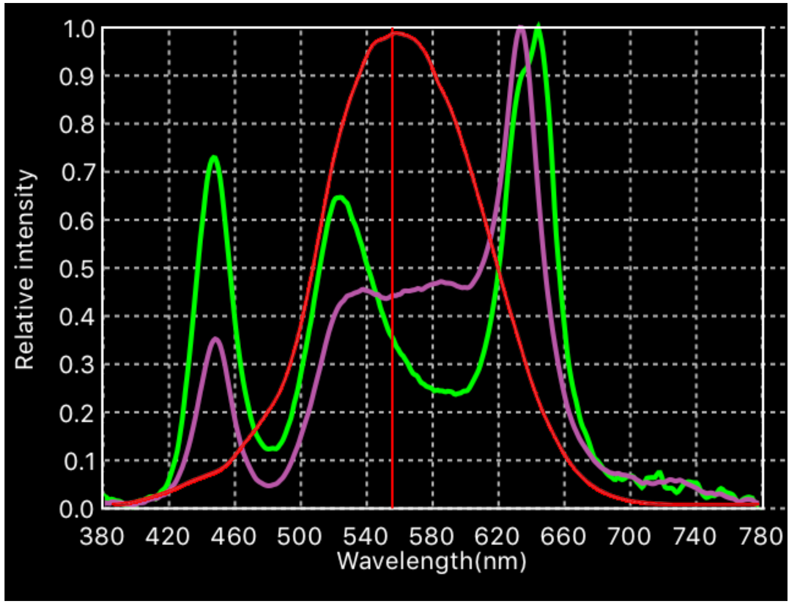


Figure 3.32: White light, paper measurement: Source 4 vs Showline

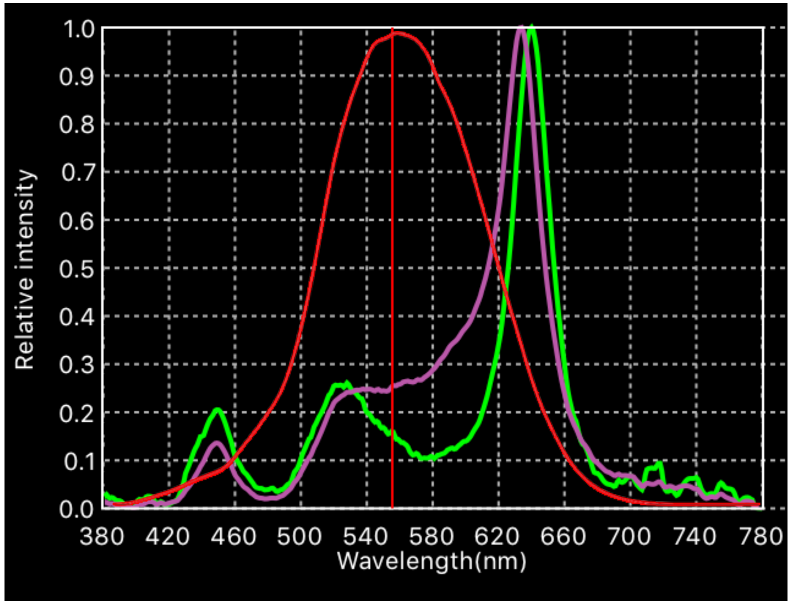


Figure 3.33: White light, face measurement: Source 4 vs Showline

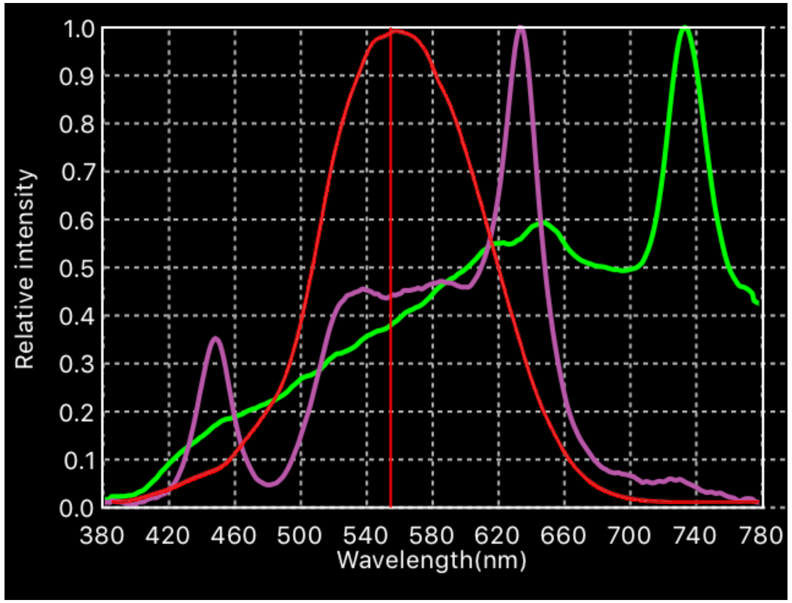


Figure 3.34: White light, paper measurement: Source 4 vs tungsten

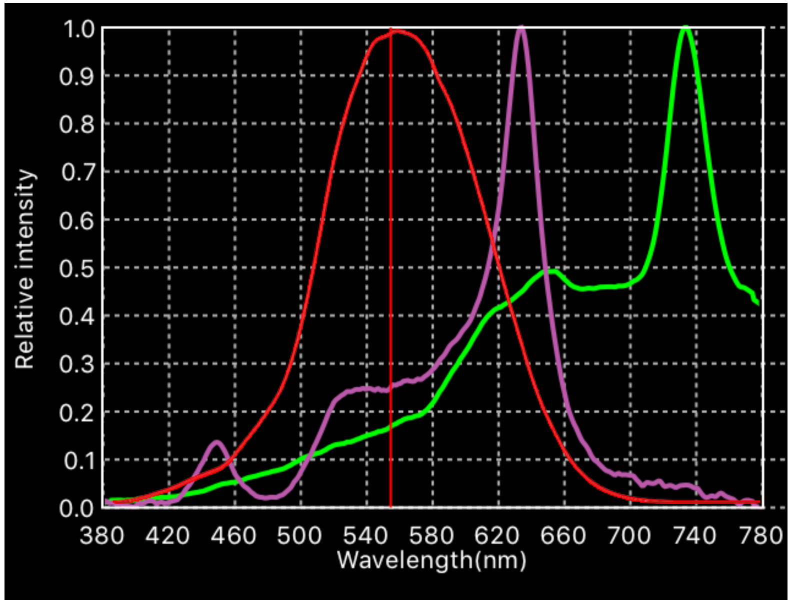


Figure 3.35: White light, face measurement: Source 4 vs tungsten

A.a. White paper colour comparison:

I t is to be noted that in this case (white preset), only the LED Source 4 and the tungsten can be compared as they share the same CCT (Figures 3.29 & 3.31). As the Showline white CCT is higher than 4000 k for the white preset (Figure 3.30), and, unlike the Source 4 it does not have a white tungsten option, it needs to respond to a daylight reference to measure the CRI, instead of a black body one. (14) In any case, it will be shown here to exemplify why a designer has to select carefully the LED's that they are working with, and to demonstrate the performance of a standard LED lighting for theater and showcase why are they no good for frontal lighting.
When people were asked to look at the the Source 4 illuminated paper (figure 3.20), mostly white was identified, with 5 times was the yellow patch VS 10 selected as a tonality. Same with the tungsten, where white was the prefered option, but with no majority of a tonality preference. Participants just labeled the paper as pure white. In the Showline LED most people chose white as the main colour, but in 3 cases participants stablished as purple blue the paper instead of white (TSC 5, VS 4 and VS 5). The paper as expected presents a much bluer tonality than the others. (figure 3.23 & 3.24)
Interestingly, when we look at the CRI, the tungsten achieves perfect colour representation except in the red tones, tone in which the LED Source 4 achieves almost a perfect score. (Figures 3.13 & 3.14) "Red is particularly important for human skin complexion" (13) However, in all of the Ri that are closer to the skin tones (R1, R13 and R15) tungsten still gets a perfect score. The biggest difference in colour quality are in the greens (R3, R11, R14), relating to both the visual and the spectrum representation.
In terms of spectra, the blue wavelenghts of the LED Source 4 peak at higher intensities than the tungsten, but dropping in the cyans (Figure 3.34), going up in oranges and yellows pairing up with the tungsten and peaking again significatnly in the orange/reds much more so than the tungsten, possibly making up with this peak with the lack of red wavelenghts in the far end of the spectrum. As explained, the CRI in the Showline should not be compared as its reference is a black body while it should be daylight.

A.b. Face colour comparison:

When focusing only on the photo, the Showline LED illuminated skin (Figure 3.23) against the other two light sources presents a significant colour change,

Figure 3.36: Shadow in the Source 4

Figure 3.37: Shadow in the Showline

being much richer in purple tones: 6 times the TCS 13 is chosen (pale pink) to define the face under the Showline, followed by TCS 01 with 5 ticks. When the skin is lit by the Source 4 (Figure 3.20) and compared to the skin in under tungsten light (Figure 3.26), the difference seems very subtle: in both of them participants have chosen mostly VS 12 and 13 (orange and red) and TCS 10 (yellow/green) to define the face. The only difference is some people choosing more of a plain yellow (VS 10) in the tungsten. It is interesting, considering that when the photos are put side by side the colours look quite different.
When looking at the spectrums (figures 3.22, 3.25 & 3.28), the Source 4 reveals a peak in blues and greens at higher nanometers than the tungsten does, specifically at 555nm the Source 4 is a point in brightness higher, and considering that that is the highest sensitivity of the eye, it would explain how the eye can still perceive some reflected green. Even then, facially wise, the greens outputted naturally by the Source 4 are certainly reduced, as absorbed partially by the skin. Same is the case in the tungsten, where a significant reduction of the greens can
be appreciated.
Interestingly, the LED Source 4 peaks in the red side of the spectrum at much higher nm inside the photopic curve (figures 3.33 & 3.35), meaning that the eye will perceive more reds coming from the Source 4 lit skin than the tungsten, as observed in the photograph, were small skin features become more visible than in the tungsten.
Under the LED Showline, the skin reflection peaks at similar values than the Source 4 (except for the blues, which peak at a higher intensity) but lacks in oranges and yellows.

Figure 3.38: Model and paper under blue LEE 119 preset S4

Figure 3.39: Model and paper under blue LEE 119 preset Showline

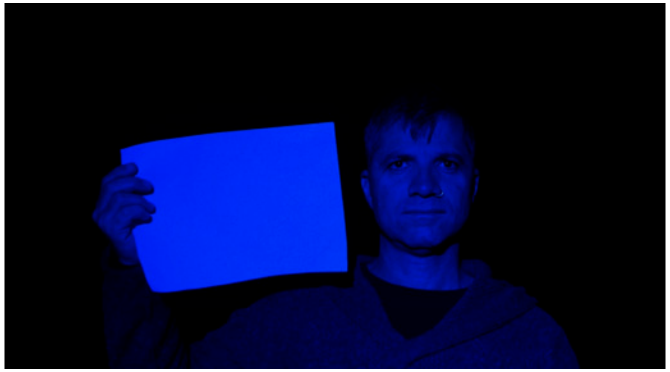


Figure 3.40: Model and paper under blue LEE 119 tungsten

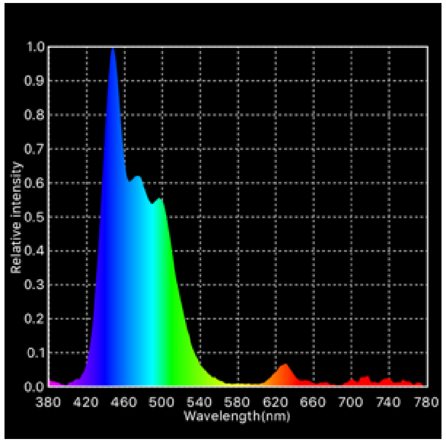


Figure 3.41: Reflected light SPD from paper in the S4

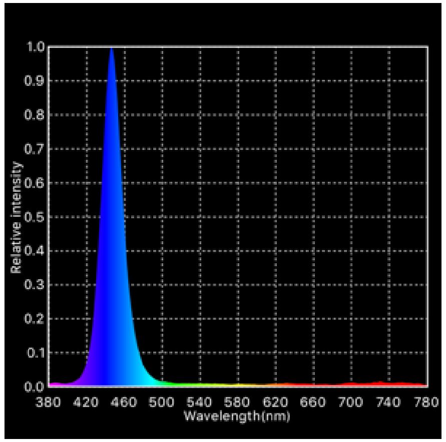


Figure 3.42: Reflected light SPD from paper in the Showline

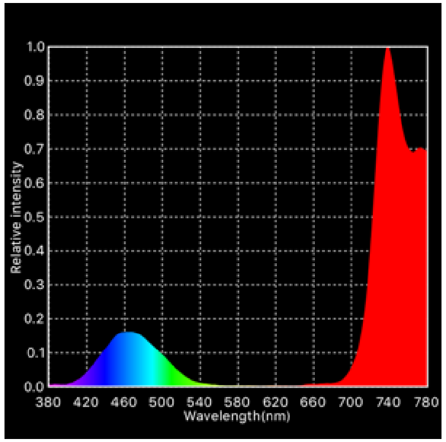


Figure 3.43: Reflected light SPD from paper in the tungsten

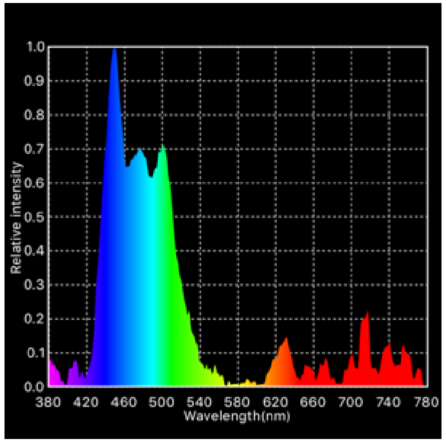


Figure 3.44: Reflected light SPD from skin in the S4

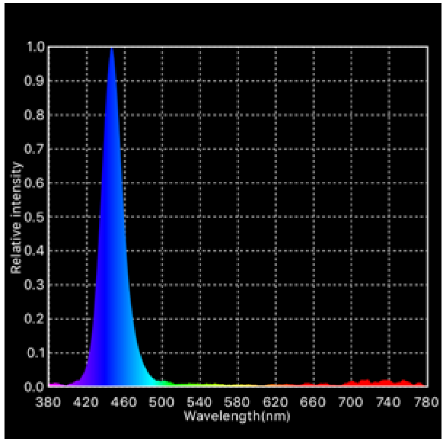


Figure 3.45: Reflected light SPD from skin in the Showline

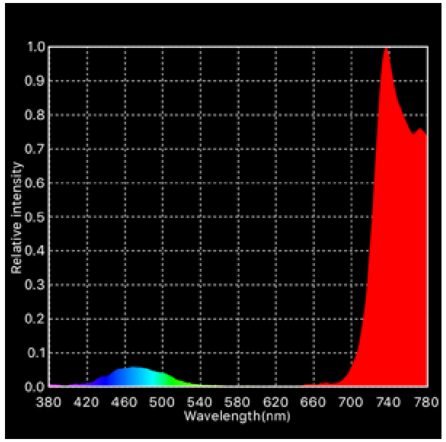


Figure 3.46: Reflected light SPD from skin in the tungsten

Comparison: Blue light

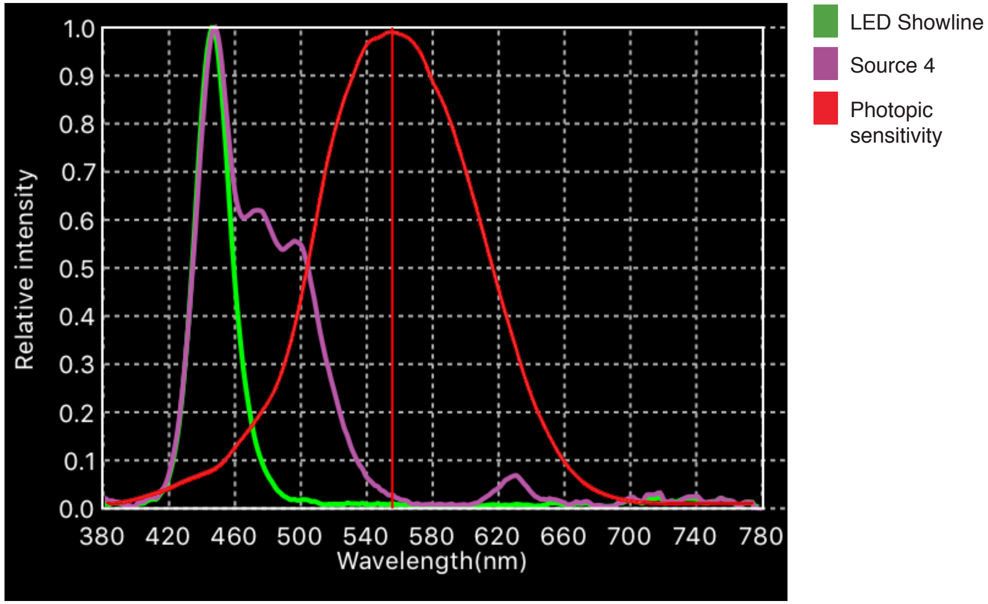


Figure 3.47: Blue light, paper measurement: Source 4 vs Showline

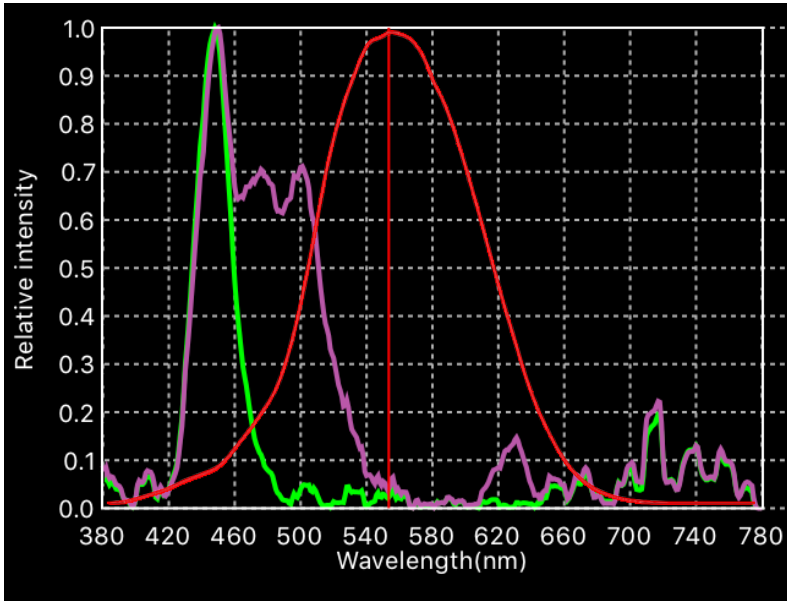


Figure 3.48: Blue light, face measurement: Source 4 vs Showline

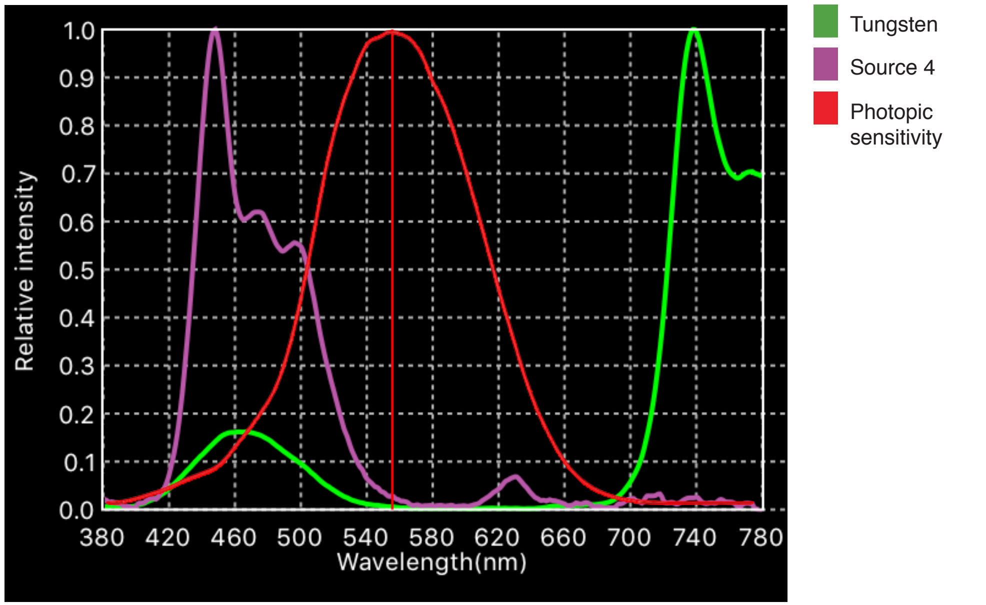


Figure 3.49: Blue light, paper measurement: Source 4 vs tungsten

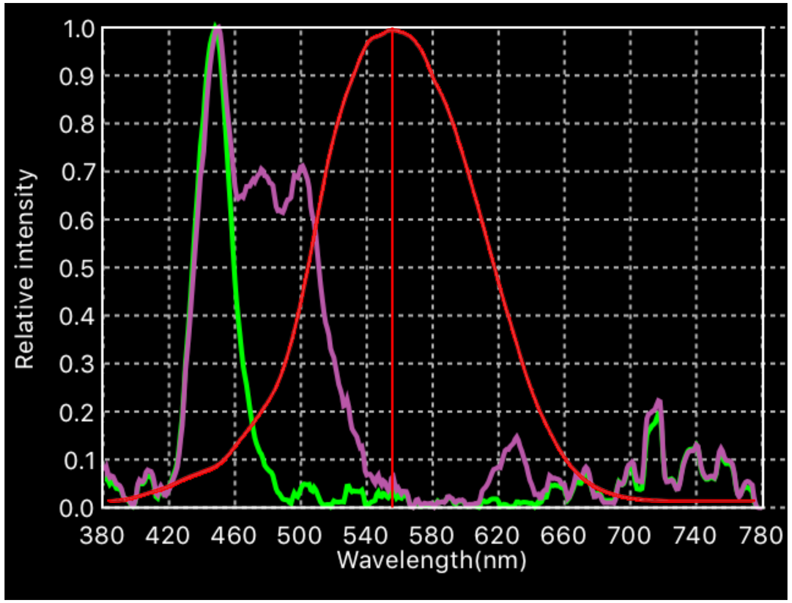


Figure 3.50: Blue light, face measurement: Source 4 vs tungsten

As as addition, a photo of the shadow that each light source delivered was taken (Figures 3.36 & 3.37). It can be observed how the Source 4 lens can concentrate several scolour chips as if it was one, delivering a sharp shadow, while the Showline, as it is lacking in lens, outputs the typical LED multi shadow.

B. Trial on blues (LEE filter 119 in the tungsten and the same board preset in the Source 4 and Showline)

B.a. White paper colour comparison:

When the participants looked at the photographs (Figures 3.38, 3.39 & 3.40), the Source 4 and the tungsten rate quite similar from each other: 6 times was the TCS 06 chosen (unsaturated) to define a dominant component in the Source 4 illuminated paper, while it was chosen 4 times it in the tungsten.
VS 2 and VS 3 (both dark blues) are the other two dominant selections in the Source 4. The Showline, however, outputs a noticeable purple tone when compared, the most selected colour patches being TCS 08 (lilac) with a majority of time being chosen, followed by TSC 01 and TSC 06 (lilac with more magenta and cyan).
When comparing them spectrum wise (Figures 3.41, 3.42 & 3.43); the physical filter used for the tungsten and used as a reference command is not a "pure" blue, but has a slight shift towards lilac. This aspect is quite obvious in the tungsten spectrum, depicting a big peak in the red side of the spectrum. However, it is to be noted that most of that peak is pretty much outside of the photopic sensitivity curve (740 nm approximately) (Figure 3.49), explaining why the eye would mostly perceive the blue curve in the spectrum, much smaller in comparison but inside the visibility range nevertheless. In the Source 4, the curve depicts very similar colours to the one in the tungsten, peaking greatly in the blues (approximately in 450nm) more than in the cyans like the tungsten does (470nm). Additionally, the Source 4 does show some small but present curves in the orange/red side of the visible spectrum of the photopic sensitivity. While the distribution of the relative intensities however seem very different, the output, as the two photographs show, is very similar; the LED sources eliminate "spilled" or unnecessary colours like the the red in the tungsten, that while emitted, will not be perceived. However, both have an important component of green that is not perceived in the photograph either; the Showline is almost completely lacking that nanometer value (figure 3.47), which seems like the eye perceives as an increase in magenta component.

B. b. Face colour comparison:

Participants rate the main component of the skin as a dark blue (VS 03) in the Source 4, while they see more of an VS 01 (dark blue with a small tint of magenta) in the tungsten. As in the paper, the Showline presents a majority of TCS 08 followed by the cyan in TCS 06.
As expected, the face, with its predominance of warmer colours, absorbs more of the blue and green in all of the light sources (Figures 3.44, 3.45 & 3.46); in the tungsten it presents a sudden peak of the red wavelengths towards the end of the photopic sensitivity, fact that may have influenced why a majority of participants have selected a dark blue with a small purple component instead of the VS 3, plainly blue, in the Source 4. The Source 4 does present a tiny red spectrum rise towards the 600 nm, that participants do not seem to notice at all. Both tungsten and Source 4 are rated as still dark blue though, and the pink or red tones have not been selected; both of them look very similar to the participants.
It is unknown why the blue, again, has a magenta look on the Showline, while there is no red or magenta component in the spectrum (figure 3.45).

C. **Trial on greens** (LEE filter 139, same preset in the Source 4 and Showline)

C.a. White paper colour comparison:

The differences in colour in this case, while subtle, seem to be when looking at the paper (Figures 3.51, 3.52 & 3.53). The majority of participants choose the patches TSC 03 and TCS 11 (pale green) to define the Source 4; TSC and VS 5 (both place turquoise) to define the Showline and VS 9 (pale yellowish green) and VS 10 (yellow) to define the tungsten. Therefore, the colour delivered by the tungsten + filter seems richer in yellow tones than the other two sources, being the Source 4 somewhere in the middle of the two.

When looking at the spectrum, both the Source 4 and the Showline present almost identical curves (Figure 3.60). While the expectation would be to find a bigger component of yellow light coming from the tungsten, the spectrum

Figure 3.51: Model and paper under green LEE 139 preset S4

Figure 3.52: Model and paper under green LEE 139 preset Showline

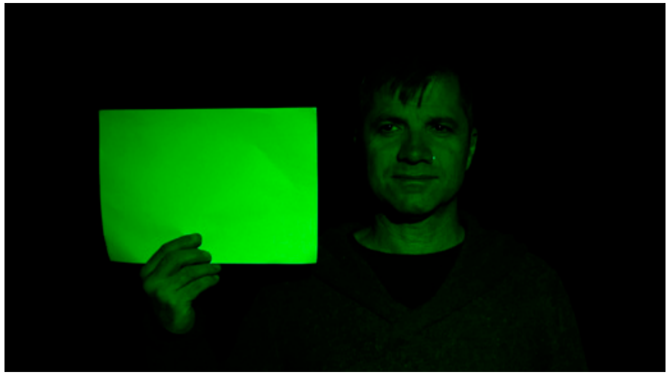


Figure 3.53: Model and paper under green LEE 139 tungsten light

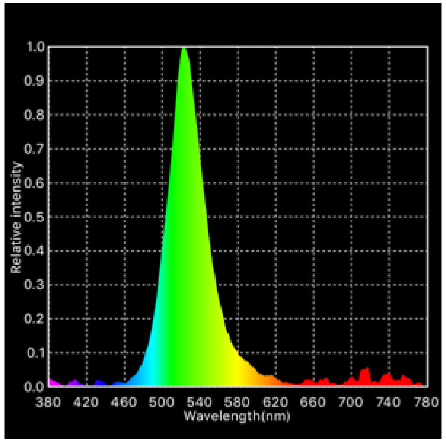


Figure 3.54: Reflected light SPD from paper in the S4

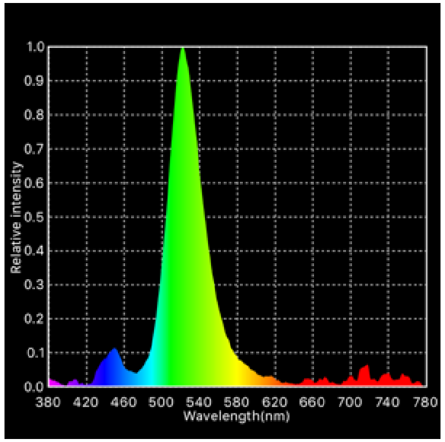


Figure 3.55: Reflected light SPD from paper in the Showline

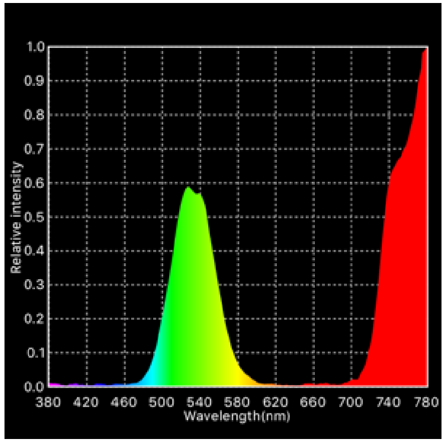


Figure 3.56: Reflected light SPD from paper in the tungsten

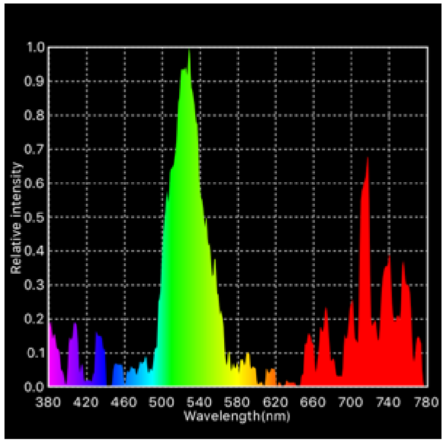


Figure 3.57: Reflected light SPD from skin in the S4

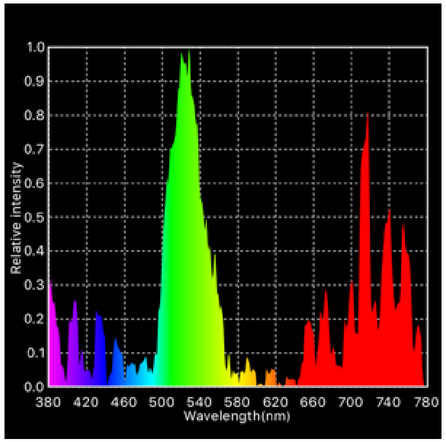


Figure 3.58: Reflected light SPD from skin in the Showline

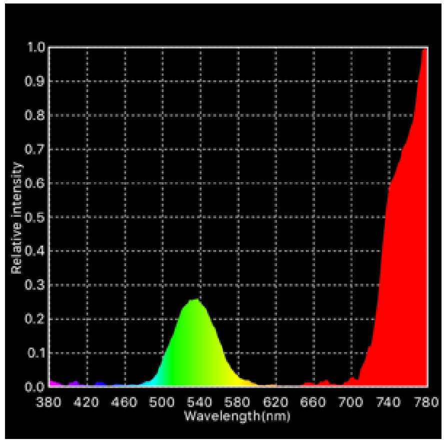


Figure 3.59: Reflected light SPD from skin in the tungsten

Comparison: Green light

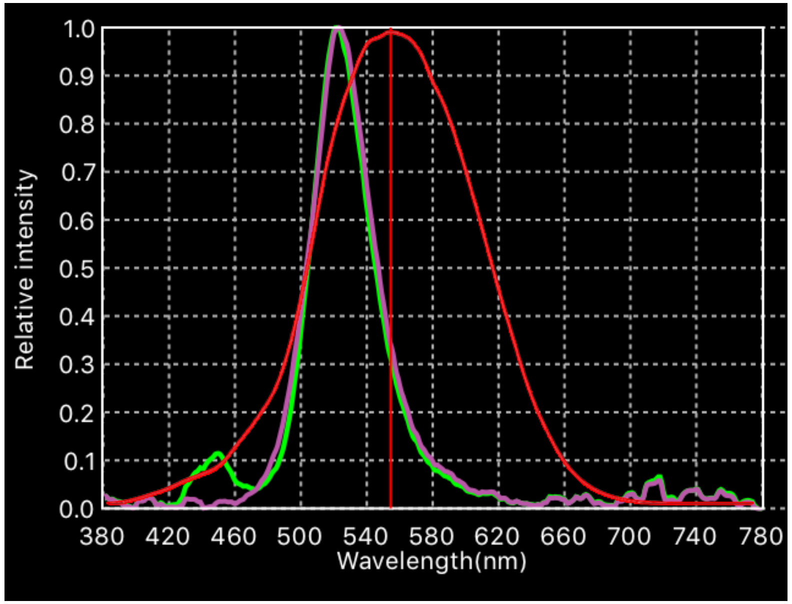


Figure 3.60: Green light, paper measurement: Source 4 vs Showline

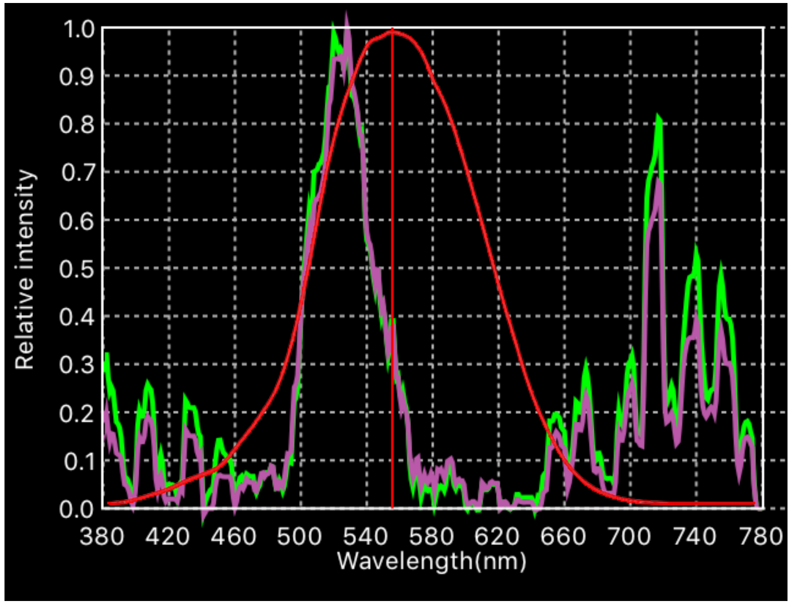


Figure 3.61: Green light, face measurement: Source 4 vs Showline

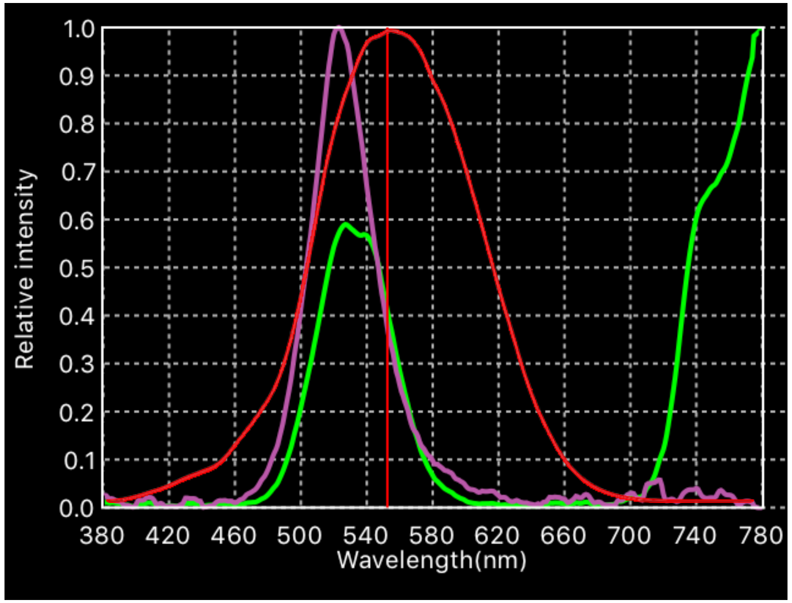


Figure 3.62: Green light, paper measurement: Source 4 vs tungsten

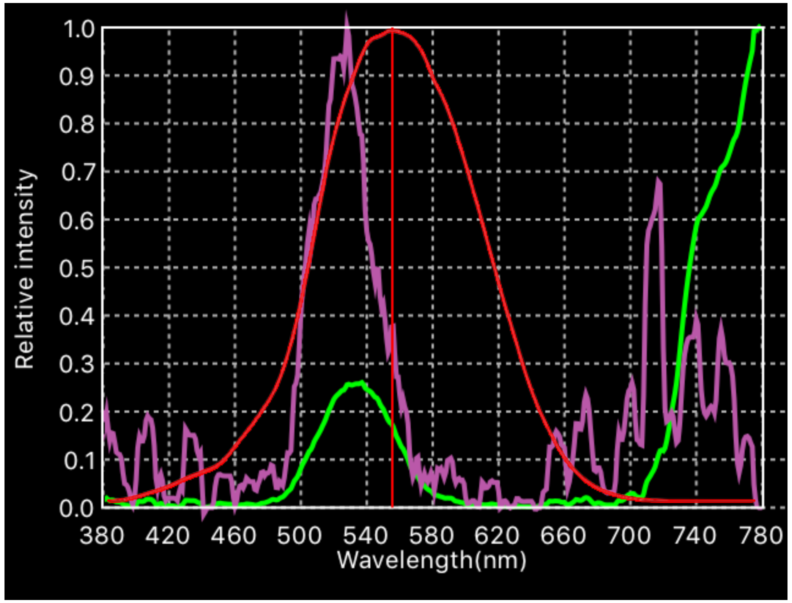


Figure 3.63: Green light, face measurement: Source 4 vs tungsten

shows something different: a very similar presence of yellow to the one in the two LED sources, but a dominant amount of red in the least visible red side of the spectrum and an almost lack of blue wavelengths in comparison to the other two (Figure 3.56 & 3.62). However, while the tungsten still presents a dominance in green wavelengths, it peaks at a lower intensity than the other two sources, arguably making the yellow side of the spectrum more noticeable.

C.b. Face colour comparison:

The change on the face does not seem as obvious as the change in the paper; participants chose mostly VS 9 (lime green) in common on the three light sources, TSC 11 (green) and TSC 4 (pale green) to define the tungsten and the Source 4, and additionally VS 7 in the Showline. Basically, all different shades of green. The spectrum data (Figure 3.57, 3.58 & 3.59) reveals how the colours in the face make the reds and magentas reflection peak noticeably in both LED sources, while on the tungsten the only perceived change is that the greens go down in relative intensity.
This particular shade of green seems in a perfect balance between the cyans and the yellows in all of the sources. However, as the photopic sensitivity is more towards the yellows (figures 3.62 & 3.63), it seems to be expected a major perception of this wavelenght.

D. **Trial on reds** (LEE filter 106, same preset in the Source 4)

D.a. Paper colour comparison

In this case is where the difference amongst all of the photographs are the least different, both in the paper and the face (Figures 3.64, 3.65 & 3.66). Participants chose unanimously a majority of the colour patch VS 13 (plain red) for the three papers, followed by VS 12 (orange).
While the spectrums of both the LED's are again almost identical (with an exception of the Showline and a small green wavelength presence) (Figures 3.67, 3.68 & 3.69), peaking at around 640 nm, the tungsten peaks in the reds outside on the photopic sensitivity curve, showing a larger relationship with the orange side of the spectrum as the difference between red and orange is less dramatic in intensity than the LED sources, suggesting that the red in the tungsten could have more of an orange tone. However, this fact seems to be barely appreciated in any of the photographs.

D.b. Face colour comparison:

When participants looked at the red light in the face, they selected VS 13 again as the main component in them all, followed by the TSC 9 (purple/red) for the Source 4, the VS 12 (orange) in the Showline and VS 14 (wine) in the tungsten.
The data from the Showline LED is missing from the SPD files due to an application error. However, the Source 4 and the tungsten are still able to be compared: (figure 3.74) in this case, there are no other significant colours which reflection increases due to the colour of the skin.

E. **Trial on ambar** (LEE filter 204, CTO, same preset in the Source 4)

Ambar and its palette is an important colour in both theater and architecture as on a practical level it is very widely used in facial applications.

E.a White paper colour comparison:

Here again, the Source 4 and the tungsten deliver a similar photographic image (Figure 3.75 & 3.77). Participants rate again unanimously (7 ticks) the paper as white, with a tint of orange (VS 11) and light pink (TCS 11) in the Source 4; same in the tungsten, with the addition of the yellow colour (VS 10). In the Showline, 4 ticks for the white, followed by several colour selections from TCS 01 (light purple) to VS 11 (light orange).

The most dominant colours on the Showline spectrum (figure 3.79) are actually red and green, with a general lack in the mid tones between the two (that is, orange and yellow wavelengths). The abundance of red and green creates orange tones by the means of mixing. Again in this case, the main difference between the tungsten and the Source 4 is a lesser presence of the reds in the less visible part of the spectrum, eliminating the unnecesary extra absorbance from the object that tungsten seems to cause. However, when the peak of the photopic sensitivity is considered, the tungsten and the Source 4 have almost exactly the same value at 555 nm (figure 3.86) and follow a very similar curve in all of the yellow/orange/red curve.

Figure 3.64: Model and paper under red LEE 106 preset S4

Figure 3.65: Model and paper under red LEE 106 preset Showline

Figure 3.66: Model and paper under red LEE 106 tungsten

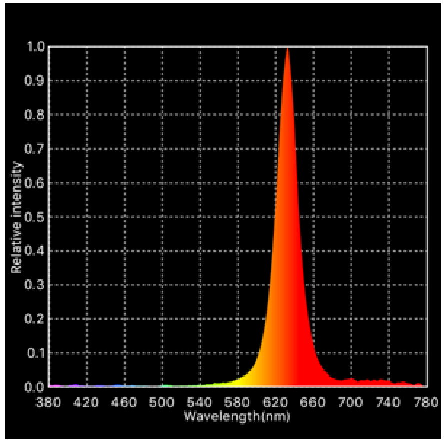


Figure 3.67: Reflected light SPD from paper in the S4

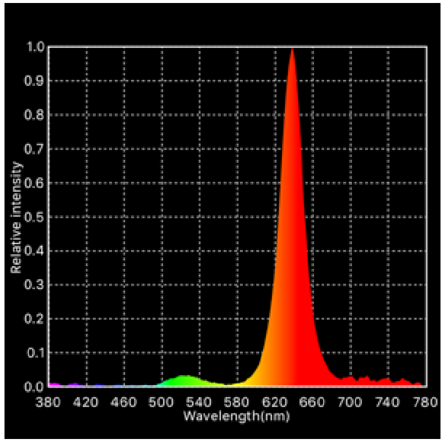


Figure 3.68: Reflected light SPD from paper in the Showline

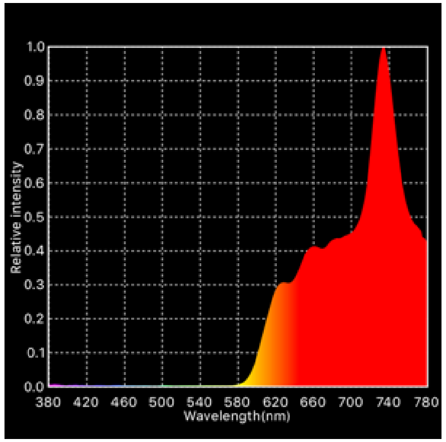


Figure 3.69: Reflected light SPD from paper in the tungsten

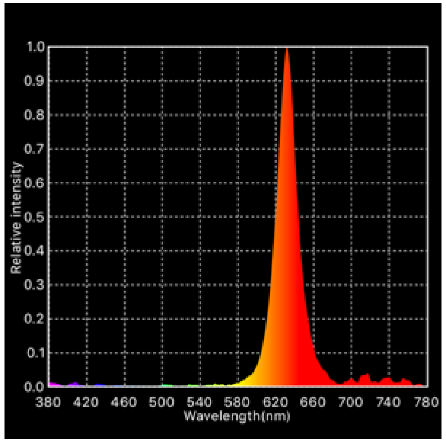


Figure 3.70: Reflected light SPD from skin in the S4

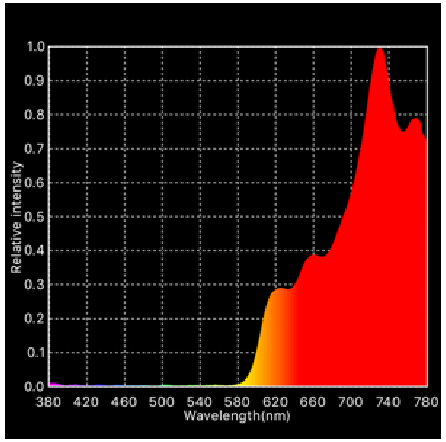


Figure 3.71: Reflected light SPD from skin in the tungsten

Comparison: Red light

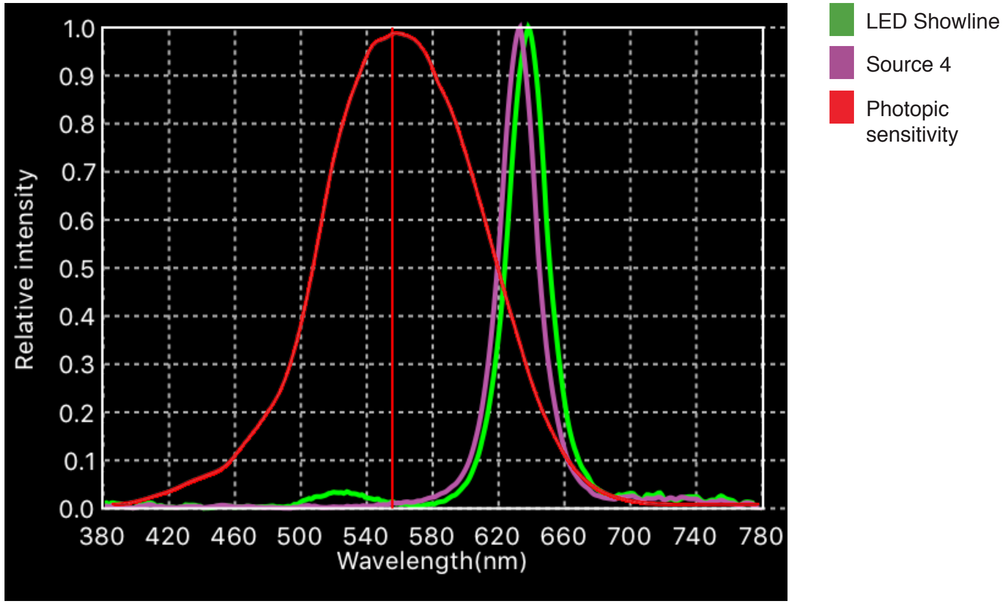


Figure 3.72: Red light, paper measurement: Source 4 vs Showline

Figure: Red light, face measurement: Source 4 vs LED (NOT AVAILABLE)

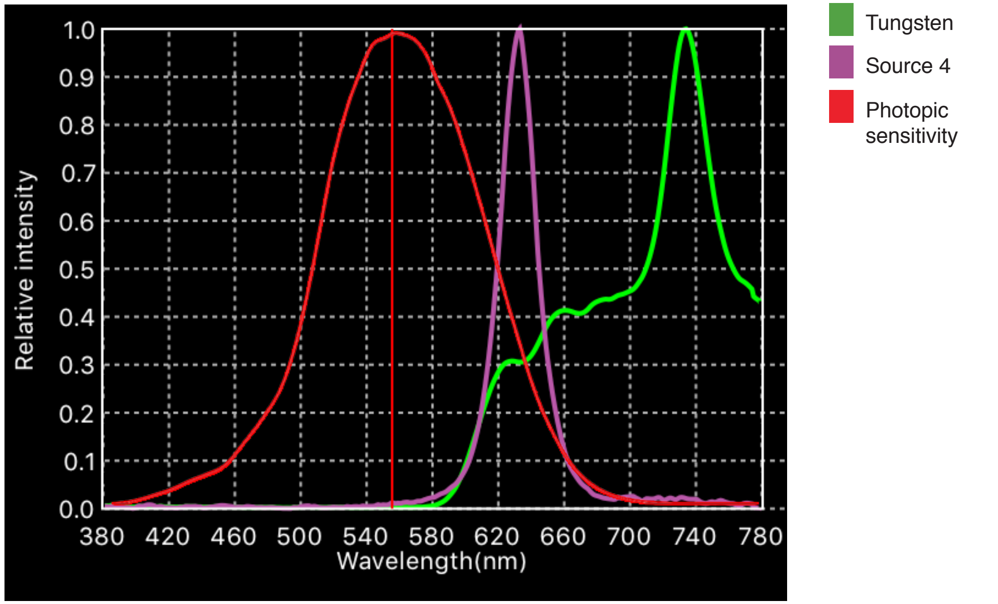


Figure 3.73: Red light, paper measurement: Source 4 vs tungsten

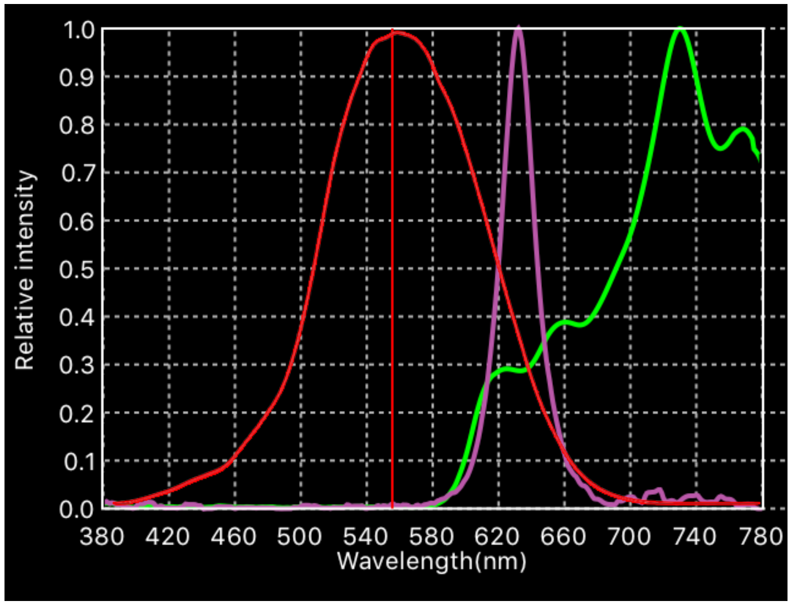


Figure 3.74: Red light, face measurement: Source 4 vs tungsten

Figure 3.75: Model and paper under CTO LEE 204 preset S4

Figure 3.76: Model and paper under CTO LEE 204 preset Showline

Figure 3.77: Model and paper under CTO LEE 204 tungsten

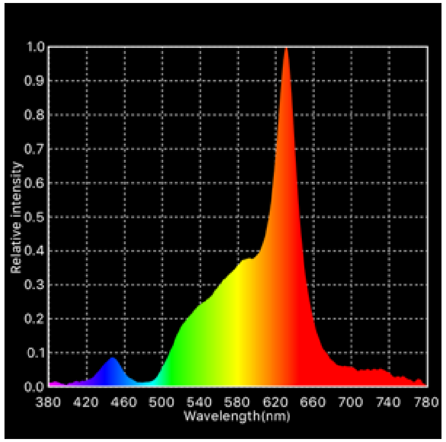


Figure 3.78: Reflected light SPD from paper in the S4

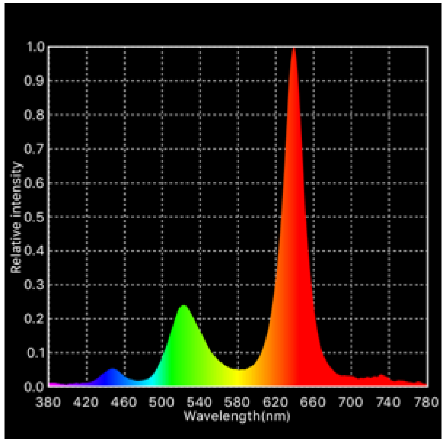


Figure 3.79: Reflected light SPD from paper in the Showline

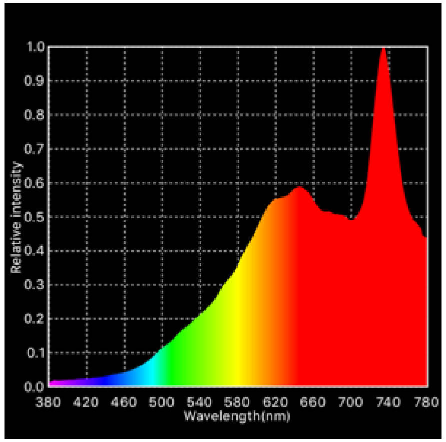


Figure 3.80: Reflected light SPD from paper in the tungsten

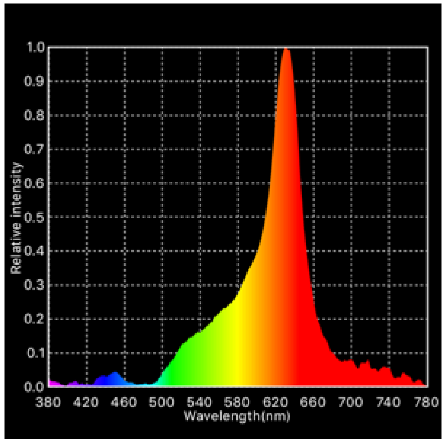


Figure 3.81: Reflected light SPD from skin in the S4

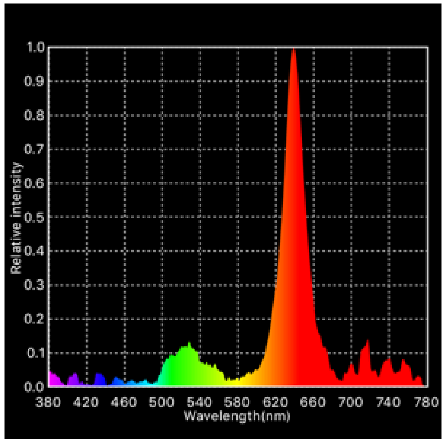


Figure 3.82: Reflected light SPD from skin in the Showline

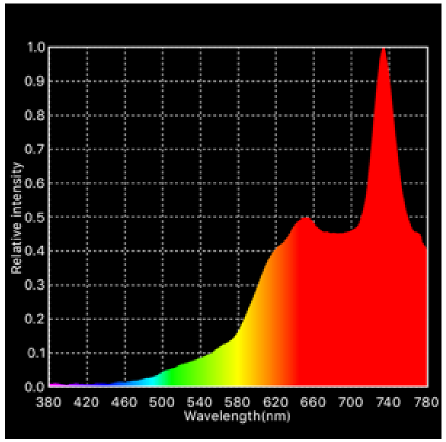


Figure 3.83: Reflected light SPD from skin in the tungsten

Comparison: Ambar light

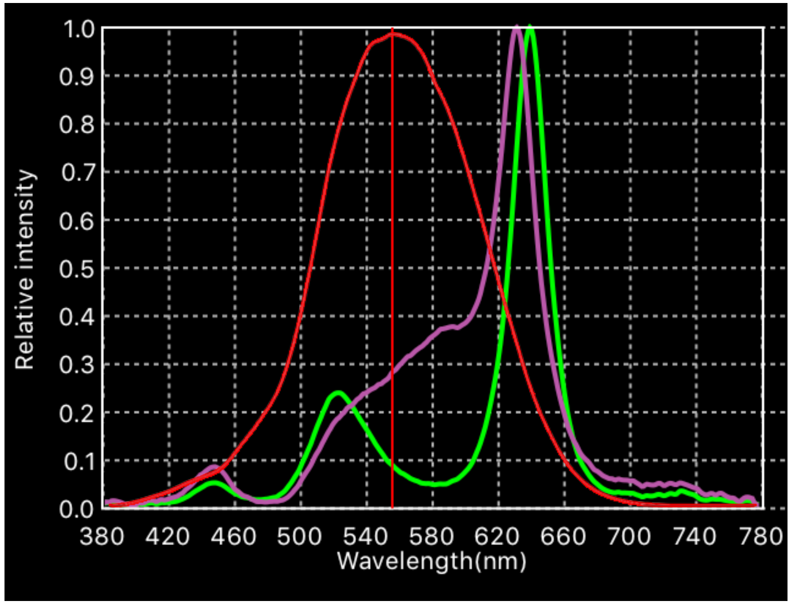


Figure 3.84: Ambar light, paper measurement: Source 4 vs Showline

LED Showline
Source 4
Photopic sensitivity

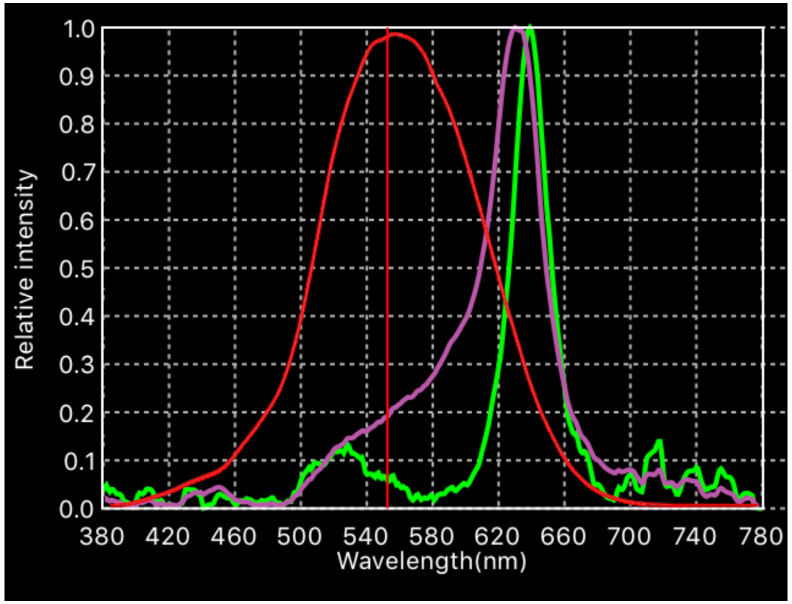


Figure 3.85: Ambar light, face measurement: Source 4 vs Showline

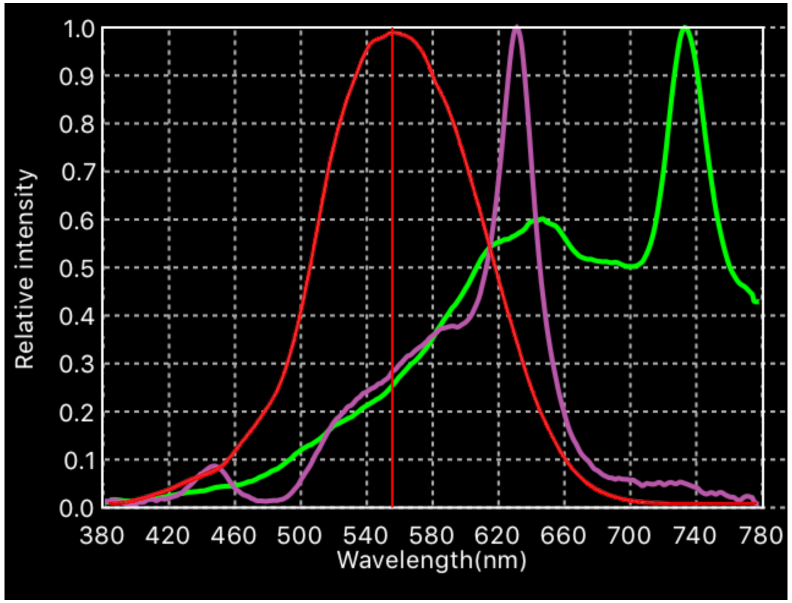


Figure 3.86: Ambar light, paper measurement: Source 4 vs tungsten

Tungsten
Source 4
Photopic sensitivity

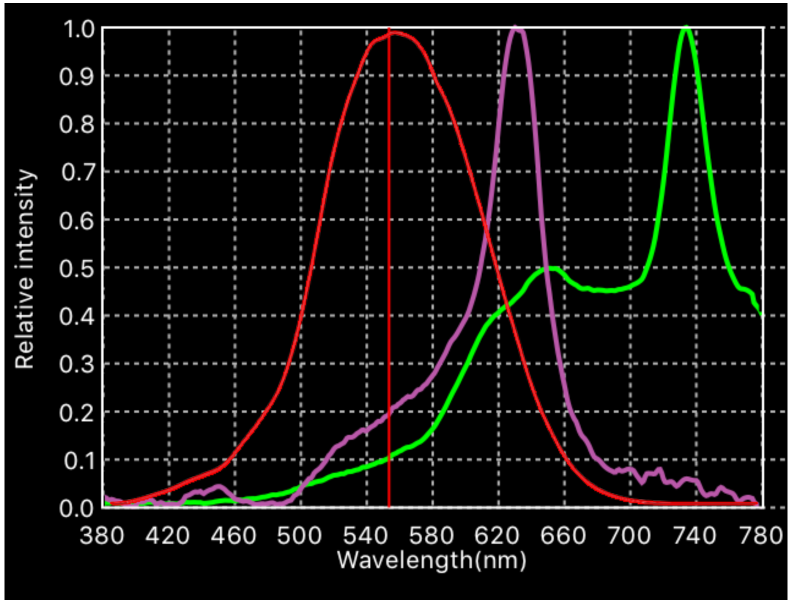


Figure 3.87: Ambar light, face measurement: Source 4 vs tungsten

E.b. Facial colour comparison:

The curve that comes before the red peaks (green, yellow and orange wavelengths) are very similar in both the tungsten and the Source 4 (Figure 3.87), radically different in the Showline (Figure 3.85), which keeps up in the greens but overcomes a noticeable valley from green to reds (Figure 3.82). Still, it is to be noted how for some reason the face seems to absorb more colours in the tungsten than in the source 4, as the curve in the oranges that was almost equal when the white paper was considered, experiences a bigger gap in the face. In the reds, it doesn't seem to matter that much the nanometers that the light source peaks at, as the sensitivity of the eye does not seem to recognize values between the wider wavelengths of the spectrum. While the SPD curves are quite different, participants recognize, in the three of the sources, a majority of VS 11 (light orange) and VS 12 (orange), with the Source 4 more shifting towards the yellows of the VS 10 and the Showline towards the reds of TCS 09.

5. Conclusions & Bias

While of course in the whites only Source 4 and the tungsten light allow for a meaningful comparison, the colours perceived in the paper in the cold white of the Showline were in many cases just plainly blue as opposed to white with a blue tonality, proving that probably the white in the Showline is not even good as a cold white source. As far as Source 4, the white outputted is still not the same as the tungsten, although participants tested to see very similar colours in the objects lit with it, which may prove the fact that if they are not used together, the white in the Source 4 delivers white correctly.

In which colours do the sources present less difference?
In the reds, the perceived difference between light sources goes unnoticed, followed by the green light, in which the tungsten's spectra delivers a higher but subtle perceived reflectance in the yellows. Yet, it is hard to tell differences between the Source 4 and the Showline. Even though the green tungsten light does not show a higher component of yellow wavelengths in the SPD, a possible conclusion is drawn about the proportion in which wavelengths peak in intensity: in the LED sources, the peak of green wavelengths per intensity outnumbers by far the amount of yellows; however, in the tungsten the green nanometer peak, while still higher than yellow, is much lower than in the LED´s (and therefore closer to the yellow in this case), possibly giving slightly more visibility to the yellow component of the spectrum. Another reason might be the fact that the eye is much more sensitive to green and yellow wavelengths, which would explain why even a small amount of yellow is perceived by the eye.
In any case, taking the tungsten as a reference, it may possible to conclude (and to be examined) that the primary colours in the Showline LED formed by green and red wavelengths (saturated yellows and oranges) will look closer to a tungsten + filter combination, while cyans, formed by blue and green, will be more susceptible of a less accurate color perception due to the blue, that seems to output a far away will be on a lower quality scale. The question is raised for magenta, being a mixture of red and blue light, since the blue outputted in the Showline does shift slightly towards magenta. The reason why is undefined, as looking at the spectrum it is clear that there is barely any red wavelength. The conclusions that can be extracted in saturated colours: Amongst LED, greens and reds show little difference between each other. While the red filter in the tungsten outputs a very similar red to the LED,s, the green filter delivers a richer colour. In any case, the difference is only significant in the blues, where the Showline delivers a blue with a tint of magenta. The Source 4 and the tungsten perceived blues are, however, very similar. It can be stated that the Source 4 does a very good job pairing up to the "tungsten standard" in terms of saturated colours. As every other colour in the spectrum is composed by the mixture of these three, it can be expected that other hues like cyans and magentas will also be delivered successfully. Furthermore, the LED only outputs wavelengths that will be perceived, while the tungsten delivers a whole range of infrared wavelengths that are "wasted" as the eye cannot perceive them. The Showline LED fails 1 of 3 colours (in the blues), making it possibly not as desirable for the representation of colours that use this hue for the mixing.
Therefore, designers will be able to substitute LED when it comes to scenery by using a Source 4, especially in applications in which colour is especially relevant.
Ambar can be considered a representation of an unsaturated coloured light: a more pastel orange, very useful when a more subtle lighting is required, not only in theater but in architecture. In this regard, again the Source 4 delivers a very good result compared to the tungsten, while the Showline is no competitor. Exploration of further unsaturated colours in the Source 4 would be the next step to follow as a complete comparison to the tungsten, and fur-

thermore, to claim the x7 Colour System of Selecon as the winner for colour representation in the LED world.
It is also clear in any case that what makes tungsten saturated monochromatic colours so rich is the fact that in the spectrum they generally show multiple peaks, sometimes of different colours than the dominant wavelength. The Source 4, while still not achieving the soft natural curve of the tungsten, presents (especially in the blues) certain acknowledgment of this fact, adding some extra wavelengths to achieve a monochromatic one. The Showline is a good example of the typically peaky LED, concentrating all of its strength on one single peak in a determined wavelength to achieve a colour.

The Source 4, with the addition of 4 more colour chips to the typical RGBW is, in any case, a much better improvement from the previous LED's fixtures tested. With quite a much similar colour approach and a programmed system that bridges the tungsten used lighting designer with the LED world, it seems quite possible to have a complete LED conversion in theater, again that is, without evaluating costs.
The main impediment to the conversion, as always, is the price: the Source 4 costs several times more than a tungsten profile. However, it is a big cost that will benefit in the long run, as there are no need for filters and being able to have the colours integrated in the same fixture results in a reduction in the number of light fixtures.

According to the SPD and the perception of the participants:
The addition of colour chips to a source that are not formed by a mixture of red green or blue, like cyan, yellow, orange and purple prove to be fundamental for the correct delivery of colours. In other words, RGB mixes are not enough. This can be seen particularly in the whites, where the Showline peaks in the three main wavelengths but the colour perceived is purple, (not even cool white) or in the ambar, where red and green make yellow and oranges but the component of orange and yellow in the sources that incorporate yellow wavelengths are much more perceivable.
The proportion in which wavelengths are mixed also seem relevant, like in the greens: participants perceived yellow in the tungsten green even though there is no yellow wavelength apparent. However, the peak in the green is closer to the yellow (and therefore lower) than in the other two sources, in which the peak of the greens peak considerably higher, indicating the relative amount of wavelengths as more important as the dominant wavelength itself.
The presence of a particular wavelength is determinant even if it's not perceived at all by the eye. This is the case in the blues in the tungsten and the Source 4, where the presence of greens in the SPD gives the impression in the image of a purer blue, (blue plus green makes cyan) while the absence of it (in the Showline) makes the subject look more magenta.

In practical uses:

The hypothesis of being able to use RGB LED with tungsten in theater as long as it is for RGB has proven to be halfway true. While the reds and the greens were very acceptable in the Showline, the blues proved to be very different. The addition of extra colour chips seem fundamental in this case for a correct colour delivery.
While, as said, It is clear that the ETC Source 4 passes the test as an LED source trying to be a tungsten, they are still not identical and cannot be used at the same time for the same purpose. However, they can certainly be used in the same space with the same colour as long as it is not at the same time, or possibly at the same time but delivering different colours in order to not be able to tell the difference. Of course, as long as the fixtures used for that one purpose are exactly the same brand and batch (to make sure they are properly binned) (Treadwell (10)) they can be used in the same space, (as seen in the theater Grant Street) as an intermediary solution. It is always important to remember that LED will, very probably, change colour over time, though that time depends on each case.

Sources of bias:

The participants asked have not seen the colours in reality, but through a computer screen, and through the eyes of a camera. Both the camera and the screen make their own interpretation of colours, reduced, again, into an RGB space that limits the possible perception of other additional colours in real life. However, as this is a comparative study, it is found more relevant that all of the photographs are taken with the same camera, with the compulsory white balance and shown with the same computer, so they can be compared against each other.
As explained before, further analysis should incorporate the full CIE colour space for participants to choose the colour from. The colour of the patches are arguably not enough to explain a full colour perception for some cases, (it is

possible to see it in the example of the ambar face description, where photographs look different but described similarly)
This test is just valid in isolation. When colours are placed against each other the perception of it changes.
The colours delivered in the LED sources are outputted by the digital version of a filter that a light board is making. It was not explored the possibility of the Showline, for example, making a different blue than the LEE version of the tungsten.

THE COLOUR DISTRIBUTION TEST

1. Introduction & Discussion

Creating scenes with colour in architecture

Having examined the quality of colour in LED and drawn some conclusions about what can one expect from it, the second approach is to take colour to the architectural space, or the creation of scenes in interior. Different possibilities of scene creation will be assessed and will be gathered to create a second test design involving colour in a spatial distribution.
It is necessary for this purpose to establish the kinds of scene approaches that are possible.

A. The creation of scenes through time

The scene creation approach takes over in many architectural setups. One good example is the job of Arnold Chan in the Hakkasan restaurant in London: “Creating the appropriate ambience also requires a very sophisticated programmable dimming system to be able to control each particular light, so we can balance the brightness of the light, on the table, on the wall, so that they become one (…) the settings change automatically. It will probably change the scene three times through the night. It’s so subtle that people don’t know it, yet the ambience at midnight is completely different from that at seven. Later, there’s much more contrast. Chan, page 35 (3). In figures 4.1, 4.2 and 4.3 one can appreciate the changes performed in the colour of the lighting througout the evening.
Another example of colour change depending on the hour of the day is Blabla’s swimming pool (figures 4.4, 4.5 & 4.6), in which the back wall and the ceiling perform an orchestrated colour palette for the swimmers.

There are quite a few technologies in the market that intrinsically aid this possibility of scene changing according, specially, to the moment in the day. Tunable white fixtures are a good example. The possibility of using tunable LED’s is already well expanded as a strip feature, alternating, for example, chips of warm and very warm white, and being able to change between the two in

Figure 4.1: The Hakkasan bar, depicting a blue light plus reflections on the wall

Figure 4.2: Same Hakassan bar, this time with more of a warm yelllow on the bar

Figure 4.3: Hakkasan bar with a green tone on the bar wall

the control system. However, that same possibility is being extended towards the LED module, introduced quite recently in the market and the star of the Frankfurt lighting fair this year (23), that with the eventual help of sensors (figure 4.7) change from one warmer, lower colour temperature to a higher, colder one, normally by means of dimming simulation. This responds to the concern in the past few years of architectural lighting with the circadian rhythms and the creation of a lighting scheme that will change with the natural internal clock of human beings. This is resolved solely to the colour temperature of whites. It could be discussed that that change is a basic link that architecture has with theater, in the way that it tries to bring the natural phenomena inside and perpetuate it with light.

Figure 4.4: Gran Elysée Hotel in Hamburg; swimming pool lighitng colour arrangement 1

Figure 4.5: Gran Elysée Hotel in Hamburg; swimming pool lighitng colour arrangement 2

Figure 4.6: Gran Elysée Hotel in Hamburg; swimming pool lighitng colour arrangement 3

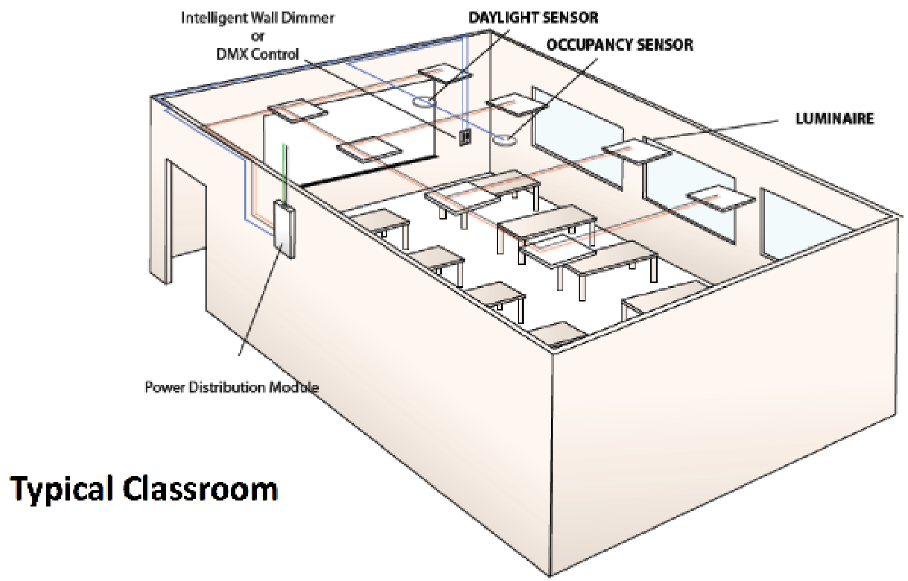


Figure 4.7: Example of layout (a classroom in this case) using tunable whites lighting for aiding the circadian rythm

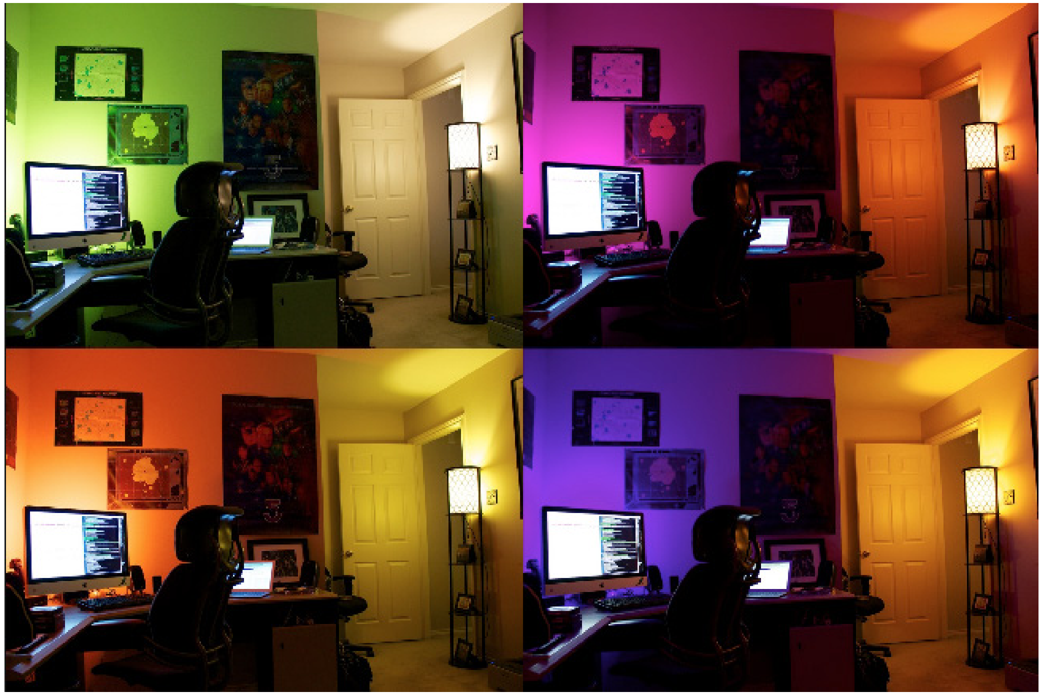


Figure 4.8: Different colour combinations created with the app and the fixtures of Philips Hue

In terms of colour change through time, in a household level there are a lot of single fixtures to choose from, like Philips Hue (figure 4.8) or Osram Lightify, designed to be used at a user level and mostly in the household, than can be easily programmed to match determined actions like music listening or similarly, time of the day.

B. The creation of scenes through the space.

This refers to the analysis of what components form a place and how to light them accordingly, instead of lighting everything equally. It is about determining the elements on the room and what are they going to be used for, so visual interest is created. Similarly, as Mark Carpenter says (3), it is about compromise: “the lighting that most strongly establishes a setting may destroy an interesting visual composition”.
This particular scene creation will be explored in the test.

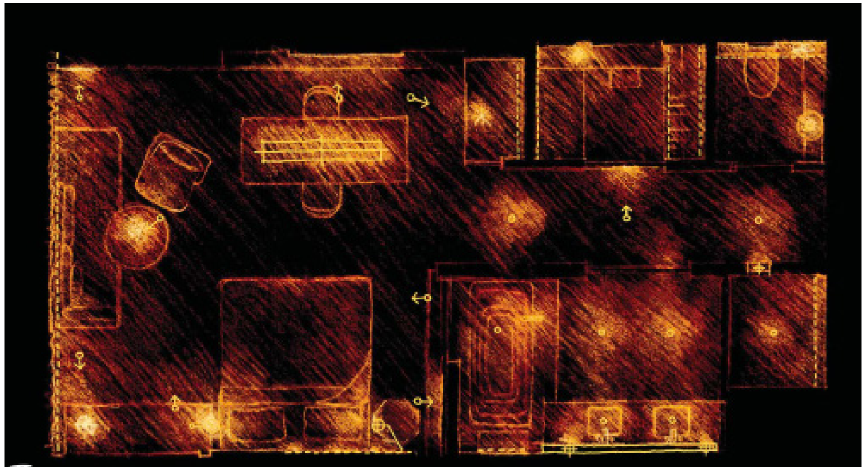


Figure 4.9: Concept drawing of a room having the intensity distribution in mind.
Drawn by The Flaming Beacon, Melbourne

2. Parameters in light to use in the creation of a scene

The question raises: the ability of applying a range of different parameters indiscriminately around a space does not mean quality. What criteria should be followed when designing a space, in order to use these available technologies accordingly? The following parameters can be mostly applied in the creation of scenes through space, although it is completely applicable to time changes as well.

1. In light intensity

We can define what elements of a room we want to be seen the most by the means of light intensity relationships, established by the means of dimming (or architectural opening regarding daylight) which surface will be predominant in sight. It is not just a matter of light power, but of the properties of the material illuminated itself, as depending on the colour it will be perceived as more or less bright. In the example in figure 4.8, it can be observed how a particular room is designed having the main spots of light intensity in mind, while also considering spilled light accross the space, establishing like that the main focus areas.

2. In colour

It is considered througout this study that colour is one of the light elements with more potential to be incorporated from theater.
“There can be little doubt that to a larger number of people stage lighting mean colour. What colour should we use for this of that is a constant cry. The use of white light or of two or three filters only is regarded as a confession of failure and immense studies are undertaken in order to use as many colours from the colour-filter sample book as possible. (...) Colour is not the principal means of expression. it is merely an adjunct to be brought in when light and its counterpart, shadow, fail. (...) There will be times when colour can be indulged in for its own sake and one must not be apologetic about it. (...) In a like manner, there will be times when colour is more important than seeing the actors.” Bentham (1).

This use of colour by the sole expressive purpose of it can be experienced in the chapel designs of Steven Holl (figures 4.10 and 4.13) and James Turell (figures 4.11 and 4.12), in which they both define new layers in the space solely by the relationship of different hues of coloured light. A chapel is an appropiate space for this design, as the need to see with fidelity is not neces-

Figure 4.10: Chapel of St. Ignatius close up, Steven Holl, Seattle

Figure 4.12: Dorotheenstädtischer Cemetery chapel close up in Berlin, James Turell

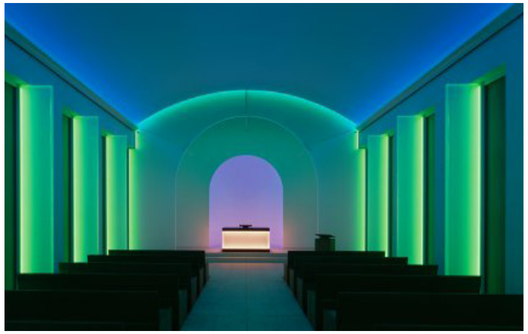


Figure 4.11: Dorotheenstädtischer Cemetery chapel close up in Berlin, James Turell

Figure 4.13: Chapel of St. Ignatius close up, Steven Holl, Seattle

sary, and it is more of a general mood what there is to be experienced.
However, When to use colour and what colours to use in interior architecture seems a legitimate question, especially since the easiness in which LED has brought colour to all sorts of spaces comes with an almost automatic danger of misuse. Everybody has experienced the annoyance of pre-programmed colour change or the use of certain colours (ab)used in applications without any apparent reason, which create discomfort in the eye and do not take advantage of the architectural textures or colours. While in theater is often to see colour used ever so carefully but yet abundantly, it is fair to establish some criteria about what makes good colour choices in architecture too.

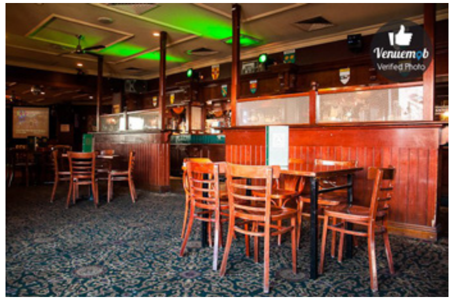


Figure 4.14: Bridie Oreillys pub in Melbourne, Australia

In this particular application (figure 4.14) a strong green light is used to light the ceiling of a room. The decision for the colour of the light (and as an extenstion, the distribution) has no foundation on the colour of the surface iluminating or accompanying any other luminic elements; when the colour is used arbitrarily it is likely to be a discomfort rather than an advantage.

“Coloured light can be misused with great ease. It is very easy to be seduced by the drama of a special effect. Even easier to appropriate the effect into a different context and find that the effect becomes meaningless. We should be careful when we consider why we want to colour light. It makes no particular sense to squirt different coloured lights all over something for no reason.” Thompson (24).

Here are some hypothesized approaches to the use of colour:

<u>2.1. The division of background and action</u>

“By isolating specific objects from their backgrounds and illuminating them from concealed light sources, lighting can be applied to alter the appearance of selected object attributes, such as making selected object appear more textured, or glossy, or colourful (...) it is possible to “create a setting in which

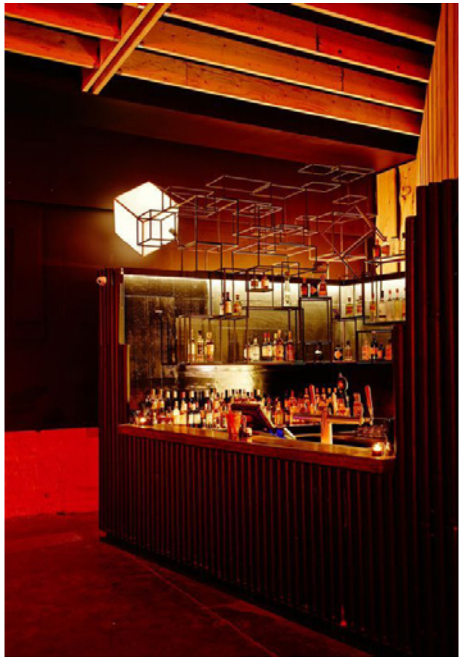


Figure 4.15: Howler restaurant of pub, Melbourne, Australia

Figure 4.16: Magic Mountain cocktail bar, Melbourne, Australia

Figure 4.17: Biba Rainbow Room in London

illumination can be directed onto selected targets to present them in high contrast relative to their surroundings" Cuttle, (25).

One criteria hypothesized to respond to this is using a good quality white light (whatever the CCT might be) in areas aimed towards people interaction, and a higher flexibility towards the areas that are meant to surround the action. There needs to be a definition, when designing, of what the activities performed in each area are and use lighting colour accordingly. Is in this matter where interior design has the most to do with theater in terms of lighting: "The perception of colour depends very much on the presence of other colours or more particularly white. A stage lit evenly all over in red soon loses its redness and is interpreted as a kind of fatiguing pink. The same red seen as a small contrasting patch on a blue stage will seem to be an entirely different colour. Colour that is to appear rich or vivid must be confined to small patches and highlights. (...) A patch of white light is our tuning fork (...) Without a white patch at all the brain flounders and can be wildly astray as to what the eye is signalling to it" (1). These two restaurants/ pubs in Mebourne (figures 4.15 & 4.16) area good example of the division of activities by means of colour: a white (warm in both cases) is stablished as a base in both, in figure 4..15 the bottles and bar area is illuminated with white while the background is enriched with red and orange tones, while on figure 4.16 the sitting areas are pale orange (benefiting the natural colour of some skins) while the back wall is lit with pinks and blues, following the colours of the image printed in the wall and making it look more vibrant.

2.2 What colours to use?

2.2.1: Colours found in natural light

"It's usually pretty safe to play with coloured light in the colours that range from blue through white through yellow to orange as all of these colours seem natural That is, they appear in nature - they can be made by heating something more or less. Moonlight daylight candlelight sunset. Dodge green and magenta unless you're really sure why you want to use these colours. (...) The tricky bit is what colour to use." (24) Thompson, unknown year.

It is true that colours and shapes derived from natural events are often very pleasant to the eye. Also, that nature has a wide range of colours in light, often mixed together (like in figure 4.18), and that colours that cannot be found naturally like green and magenta shold probaly be avoided for the very same reason. In the Biba Rainbow Room in london (figure 4.17) one can see the application of a sunset palette in the ceiling coves. At the same time, this room is also a good example of considering different surfaces in a space like the "back-

Figure 4.18: Natural colours found on a storm in at sunset

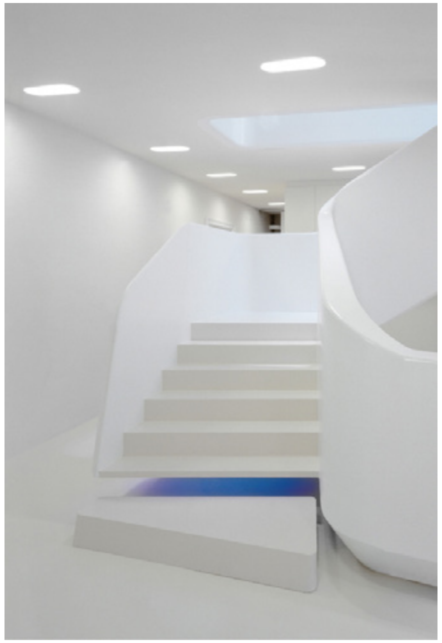


Figure 4.19: Jelitzka Partner office designed by XAL in Vienna

Figure 4.20: Nivea House by XAL

ground".

"Colour, like softness, is one of the qualities of light which can be externally manipulated and so working with the colour of light in an environment will change the perception of it. (...) Light colour has enormous influence on the way we perceive the mood of a place.

Coloured light on its own it's rarely effective (...) usually some coloured light will tell a story more effectively if it is able to be compared with something else. The eye/mid partnership can turn an environment totally illuminated by blue lights back into a normal white environment, but if there is a bluish accent within a space which is otherwise lit with white light, the colour of the accent will remain recognisably blue against the white reminder. In fact it can be very nice to have a warm coloured general light and then allow the accents to stand out by colouring them a little blue." Thompson

The office lobby in Figure 4.19, designed by XAL, depicts very well this addition of colour to a otherwise fully white lit space, adding dinamism to the whole composition. Another example seen in figure 4.20, also by XAL lighting, uses blue in the ceiling coves. In this case, not only is creating a similarity to the blue sky, but introducing a branding factor: Nivea products are always blue.

"When designing a space, imagine the colour of the light in the yet to be built space. Imagine a contrasting coloured light accent to support a contrasting architectural idea. Can similar architectural ideas be linked more strongly by similar light colour?(...) Colour is only one of the qualities of light which can be externally influenced to support an idea."
(24) Thompson.
"Natural light is the benchmark for all the artificial alternatives. What we instinctively enjoy about daylight is its variety. (...) If natural light can provide us with an instinctive appreciation of variety, it can also demonstrate how tedious and uncomfortable uniformity can be. Beneath a dull, grey overcast sky in a northern latitude, shadows are softer, form is indistinct and colour is more muted: life can seem less exciting and the overall effect can be oppressive. (...) Recognizing the positive and negative associations of both natural and artificial light in an important step towards creating a good lighting scheme.(...) The aim of good lighting is not merely to enable us to see what we are doing once the sun goes down. It is to provide a richness of visual experience: both the subtlety and variety we enjoy in natural light, and the sparkling magic of light-filled celebrations." (6)

Figure 4.21: Gleneagles Hotel Spa, designed by Amanda Rosa, Scotland

2.2.2 Colour by co-existing elements in the space

Also by the experience in working in theater, it was very common to see designers using coloured light matching the object that they wanted to illuminate. Since the colour of the objects seen depend entirely on the light that hits their surface, it is logical to establish a similar way of proceeding with interior architecture.

"The fact that illumination places the intrinsic colours of objects in a different light or, in other words, can make them appear in a different colour, play an important role in marketing, merchandise presentation and interior architectural design. The desired colours must always be seen as dependent upon the colour of the illumination." Bachmann (27).

It is hypothesized that for lighting as a whole, the colour of the individual objects must be considered. In figure 4.21 one can see a basic example of this criteria: the wood, rich in warm colours, is illuminated by a very warm white light, while the pool is treated with colder white light, richer in blue wavelenghts.

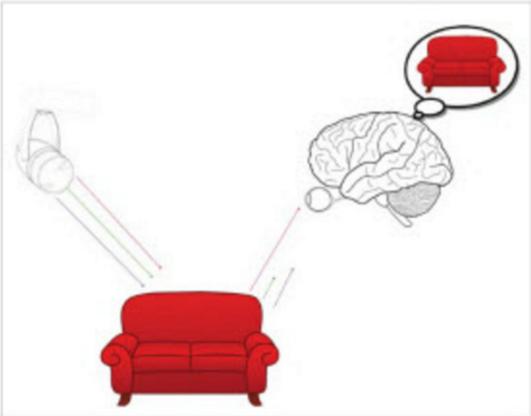


Figure 4.22: Bridie Oreillys pub in Melbourne, Australia

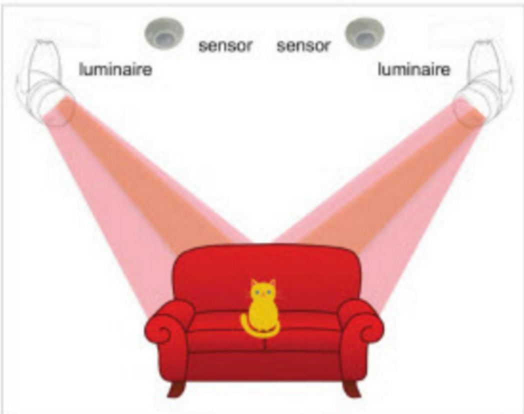


Figure 4.23: Technology used in the intelligent lighting being developed to addapt the SPD to the material colour

As seen in the scheme in figure 4.22, the eye perceives only the wavelenghts corresponding to the colours present already in the material of the sofa.
Considering this approach of lighting as a combination of the colour of the light itself and the surface that is hitting, there is a new technology in development that responds to this idea of having intrinsic colour of objects as a design parameter and changes light accordingly, with the aim of minimising energy loss from absorption (figure 4.23).
"In LED (...) the spectral power distribution can be customised. Combined with existing sensor technology, it is technologically feasible to develop lighting systems that sense the colours of objects within a space and tune the SPD of directed light to maximise reflection and minimise absorption, thereby reducing energy loss. (...) A white light source emits light of many different wavelengths, but colored objects absorb much of the light of some of those wavelengths. (...) If the SPD of the light source had spectral characteristics more similar to the light that is reflected from the object and perceived by the viewer, less light would be absorbed. Light absorbed does not contribute to the visibility of objects in the space. For illumination purposes, the absorbed light is a waste of energy." Davis & Durmus (28).

Questions raise of this system, like what would happen when someone with coloured clothes would sit on the red sofa. While this technology is still in process, makes sense to apply the concept behind "manually" as a design criteria. Results of the testing also show that the energy could be substantially decreased by using this system.

3. In distribution

As a lighting designer, one of the first things taught are the amount of lux in a surface plane necessary for it to be effective for people to see. There is a very broad information and regulations that are based on the horizontal plane. It is a general consequence of architecture in terms of lighting to wash and flatten a whole space in order to respond to a wide range of uses and necessities. However, paradoxically that often results in a space that does not cause comfort in its users and does not take advantage of the human centered possibilities.

Figure 4.23: Boxing Wellness Center, MW Design, Taipei

"Regulations always dictate that you need certain light levels on horizontal planes, but that's only half of the story, because if you only light horizontal planes and no verticals, you get a headache after a while.(...)it's very comfortable to be wrapped in light. If light is coming from above, it's rather boring and doesn't engage with us very well. Whereas if you've got light from below, from the sides, from above, so that you are enveloped in light, it's a comfortable feeling." (3) Chan

In figure 4.23 one can appreciate the different distributions that comform the reception of this Wellness center in Taipei. Each element is lit individually, using luminaires that respond to each particular shape. There are spotlights that guide the user into the computer, while the contrast is kept by not having addional downlights where they are not needed.
Of course, it can be argued that it is not the same to light an office than a pub. However, horizontal lighting in offices is many times synonim of an un-welcoming lighting, fact that takes to the question: could be the distribution of a whole be considered in different ways, paying attention to the individual details, rather than downlighting exclusively?

"While it is a fundamental assumption for general lighting practice that whatever needs to be seen is located on the horizontal working plane, and that people's visual needs are provided for by applying the specified illuminance level uniformly over that plane, it follows that efficient lighting applications will generate harsh, unattractive down lighting effects for the occupants. (...) what is needed is fundamental reassessment of the purpose of lighting. (...) Uniformity is not a criterion of lighting quality and should be purged from our standards. For efficient lighting, direct flux needs to be incident on surfaces that will reflect high proportions back into the space. Of course, a given MRSE (mean room surface exitance) level can be provided by downlighting, but in fact, in any conventionally decorated space, uplighting is several times more efficient than downlighting. Other lighting distributions, such as wall washing and even display lighting, that are conventionally thought of as inefficient or even not relevant to general lighting, can in fact make effective contributions to MRSE. Beyond that, skill in applying lighting comprises devising distributions of non-visible direct flux that will create predetermined distributions of visible reflected flux." Cuttle (29).

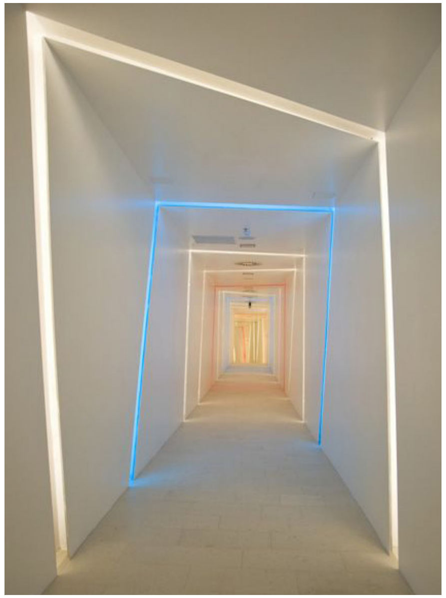


Figure 4.24: Warm conneciton installation by Skira Studio

Figure 4.25: Bond Street 2, resicence design by John Pawson

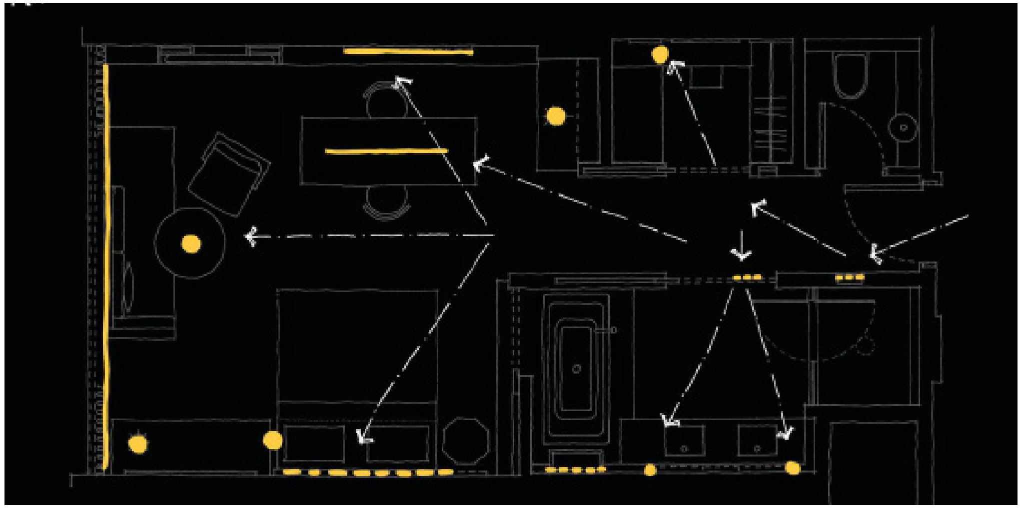


Figure 4.26: Guest experience sequence of a room designed by The Flaming Beacon, Melbourne.

An example can be seen in figure 4.24, where the space is illuminated both horizontally and vertically by linear lighting that follows the space assimetrically. Addionally, the white on the walls reflects the light, reducing the need for more powerful fixtures and allowing the designer to use more expressive mediums.

LED brings a whole new range of possibilities in flexibility to aid this criteria. Therefore, it allows to consider the different elements of a space as different additions of a composition: like in theater, it allows to consider the "actors" and several "stage" factors.

"We can now put light in places that we couldnt put it before, and we can now arrange it in ways that we couldnt. Its much easier to get lines of light, and circles, and curves and organic shapes and non-linear shapes. (...) I can be more artistic as a designer because ive got much more to choose from." David K. warfel, page 10 (30). In figure 4.25, lighting under the steps demonstrate the wide capacity of lighting designers to illuminate any element imaginable, creating interesting effects like the "floating surface" seen in the photogarph and contributing to a mood with the blue wash on the walls as a companion.

Arnold Chan: "The most important thing is what I call the hierarchy of light. You need to know where to draw people's attention. In the case of a restaurant like Hakkasan, the focus is first of all the table. You need to read the menu and see what you are eating. Then your attention is on the people you are eating with. You need to make the visual appearance of people flattering so they feel comfortable. When they feel relaxed, then there's every chance of them enjoying the whole experience. Then they look up, they catch glimpse of theater around them (...) they can see other people, they can see the highlights of the detail." (3) Chan.

The drawing in Figure 4.26 is a good example of trying to establish a hierarchy: in it, lighting designers from The Flaming Beacon company created the lighting scheme of a room according to the possible movement and vision direction of people around it, in order to determine the lighting needed in each sub-space of the total.

To the question of how did he chose to light people (the actor), Arnold Chan said:

"Reflected light. None of us look very good when lit directly . Photographers (...) bounce light to create a softer appearance". Chan, page 41 (3).

"Regardless of the process used to calculate the lighting design, the fundamental requirement is that the designer achieves the appropriate luminance distribution on the vertical surfaces. Lighting is all about the luminance of vertical surfaces and they will not just happen as a by- product of horizontal illuminance. " McLean, page 9 (6).

Gathering all this information results in the test design.

3. Test design

The test main approach will be to put in practice the SPD sensor technology explained in the previous chapter of selecting the colour of light according to the object, a technique also very much used in theater. Addionally, it will also explore an alternative to horizontal illumination.
The space will be treated according to the following theatrical guidelines:

"A principal source of light is chosen whose characteristics can be used to establish a basis for the primary lighting objective (the actor in theater, the person performing the activity in interior architecture). Usually, we are concerned with the effect of this light source upon the foreground center of interest, an actor, a product. The background is lighted separately from the foreground so that a balance between the two can be easily achieved. The next step is to choose a secondary source to act as a complement to the primary source. Its purpose is to enhance the effect of our principal source and aid in conforming to the limitations of our media. In theater it might be a cold acting area light placed so that the warm acting area light is more predominant. All other lighting sources can be grouped together. Their purpose is to provide small area interest-icing on our lighting cake" Levin, page 87 (31).

In interior architecture, having this separation in terms of lighting is not that difficult as by the distribution of a space there is always areas designed for people to perform certain activities, while there are areas more void of a specific use or where actions happen but they are, in nature, of a more reduced time. Therefore, while things do not happen under a measured script like in theater, it is possible to establish some assumptions of where particular actions will happen, and assign lighting accordingly.

On one hand, it is hypothesized that walls can act in most cases as "the background", while furthermore lighting vertical surfaces and paying attention to reflected surfaces rather than direct lighting is much more effective in terms of brightness. Basically, lighting in a more dedicated the level a lot of elements of a space is better than giving the same treatement to the space as a whole. Also, the addition of coloured light will result in the present colours becoming more apparent and stimulate the viewer to remain longer in the windowless room.

On the other hand, 3 levels of colour quality exigence are established:

a. High level of interaction: eating, writing, working = high colour quality of light. halogen or similar LED SPD distribution and intensity, as it is where "the actors will perform"

b. Medium level of interaction: relaxing, drinking. Possibility of unsaturated lighting. If reading, add an independent separate lamp.

c. Low level of interaction: Fully coloured light possible (saturated), but a compromise between the general mood and the colour of the dominant objects involved.

Possible colour palettes: natural phenomena: oranges, blues, warm whites. While nature colours seem the safest to represent, they also seem the hardest to achieve, as the colours that (especially) LED naturally produce with more fidelity are the saturated colours. However, most colours in nature are quite soft and pastel (unsaturated). Pastel seems a correct approach in many ways: it has a stronger colour component than simply white with different colour temperature (some very warm whites could be defined as unsaturated oranges) but also, allows human interaction to an extent (of course when difficult visual tasks are not involved) by not completely eliminating the white light component, that allows the skin to reflect more of its more flattering colours.

All of these criteria are subject to the existence of different activity components. In some office spaces, especially if they are small, the different treatment of the objects in the space would not only be unavailable but also with a lack of purpose.

3. Test setup

This test will be based on the basics of use of colour and distribution, and will focus on a criteria of corresponding to the placement and colour of objects in-

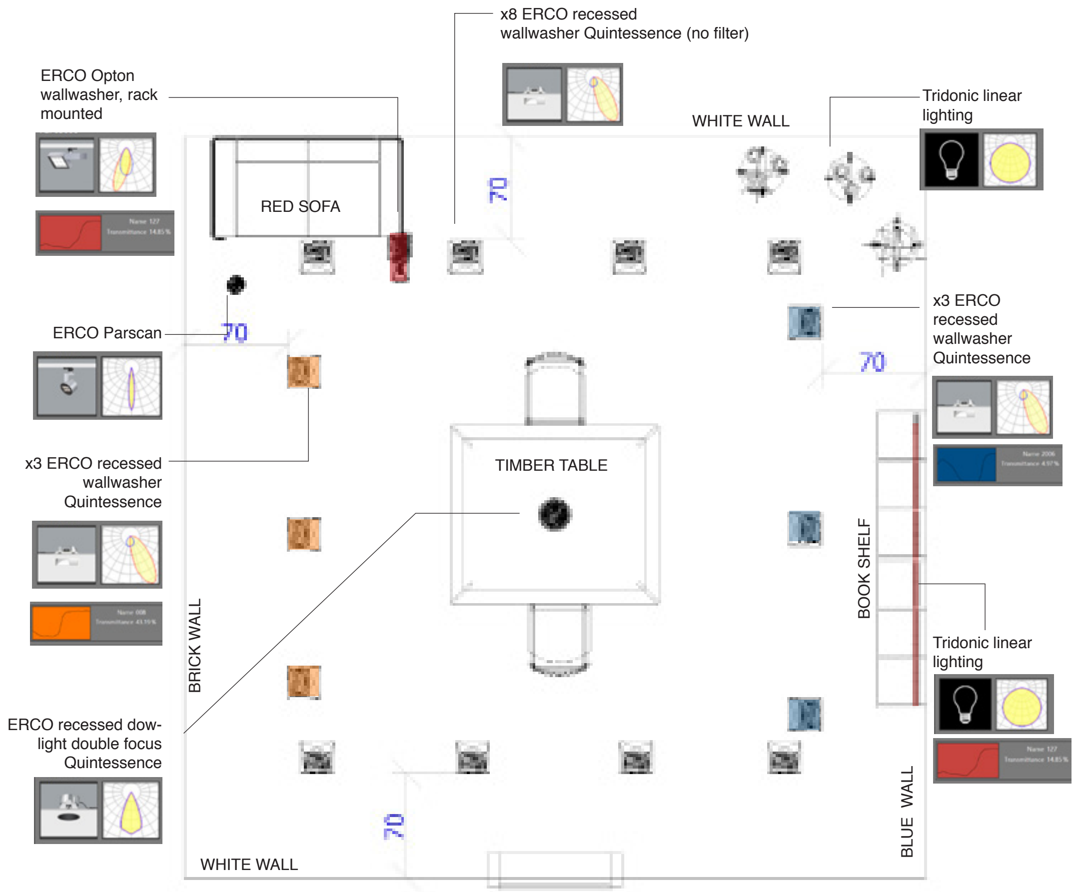


Figure 4.27: Top view of second and third lighting layouts (A & C in the test). The second one (A in the test) will be the same but without the colours. Schematic only.

stead than to a general concept or mood. Its aim is to introduce at a base level different colours and distributions as opposed to only horizontal lighting as a possible alternative to an space, and investigate the effects. The purpose of the space created will be rather undefined, maybe reminding of a lounge for the furniture placed in it, as a question made to the participants will be what action would they perform in each lighting situation. As explained, the test setup will be based in a square room, 5m x 5m and 2.8m tall with no windows with a central table and two chairs, considered “the central action space”, and some added elements like a sofa, plants and a bookshelf, all of which will have different light treatments, according to their shape and colour. All of the other space that is not the main “action table” will be considered the background.

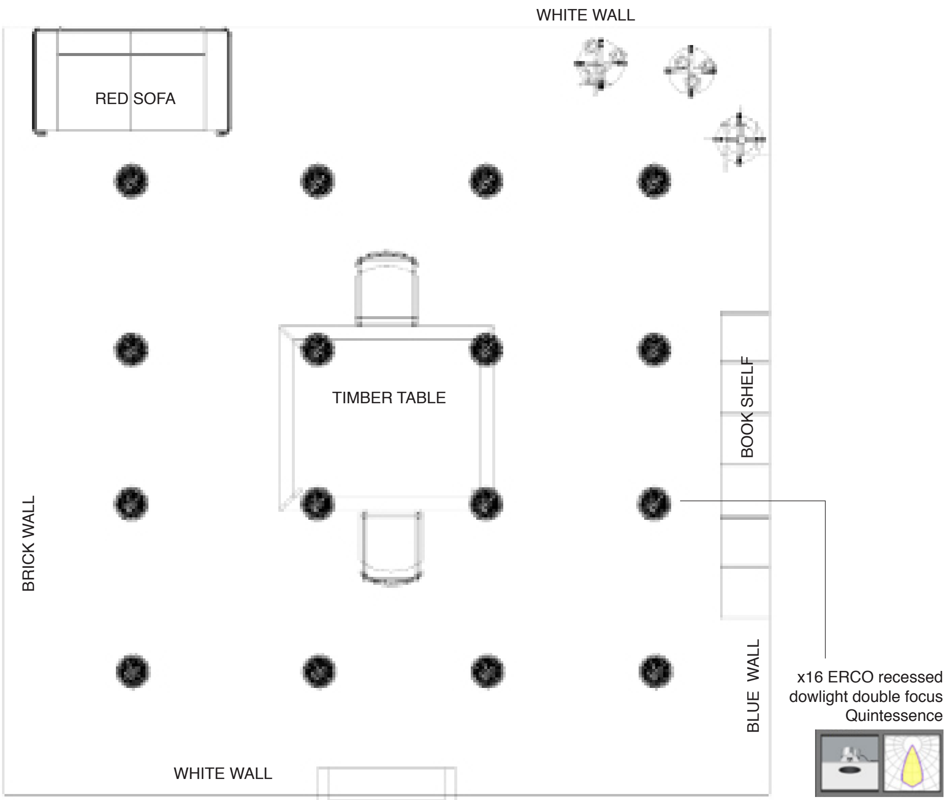


Figure 4.28: Top view of the downlight room (B in the test). Schematic only.

Four different views of the room will be shown (one per wall) and participants will be asked the same questions in the four photographs.
As the table is established as the main action area, lux are measured. In the downlight room (room B) the levels are around the 1700 lx (figure 4.30), while room A & C (the wallwasher rooms) they are around 700 lx (figure 4.31).
The main surfaces illuminated have the following reflection factor:
- The white walls: 88
- The timber table: 56
- The timber floor: 65
- The brick wall: 21
- The blue wall: 12

Additionally, 2 of the 4 the walls will be white, while a third one will be brick and a fourth one ultramarine blue. The aim of the change is to explore different lighting in different colours and textures and how do they influence each other. All the fixtures used will be ERCO, with a CRI of 91 and an SPD very similar to the one delivered by tungsten (figure 4.29). 3 different setups of rooms will be shown to the sample of people. The first one will only have horizontal white wash (downlights)(figure 4.28) , like typically seen in offices etc. The second one will have dedicated lighting: wall washers on the walls, spotlights on the table and sofa and linear lighting in the plants and the bookshelf, but everything in a white warm colour. (figure 4.27 without the colour filters)
The third one will be the same distribution as the second one but will incorporate the addition of colours to the second setting: the wall washers of the brick will try to pair up the

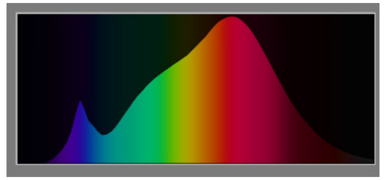


Figure 4.29: SPD of the ERCO Quintessence series

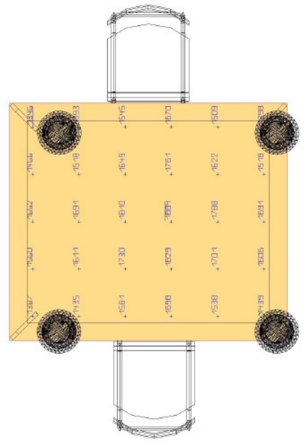


Figure 4.30: Lux levels of room B on table

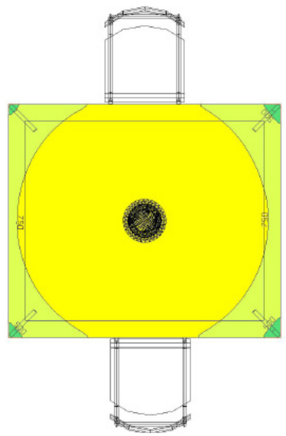


Figure 4.31: Lux levels on room A & C on table

Room A

Room B

Room C

Figure 4.29: First image shown to participants.

Figure 4.30: First image shown to participants.

Figure 4.31: First image shown to participants.

Figure 4.32: Second image shown to participants.

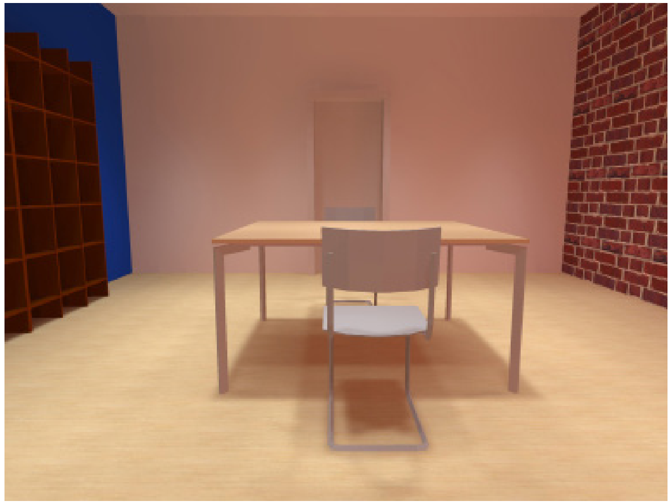


Figure 4.33: Second image shown to participants.

Figure 4.34: Second image shown to participants.

Room A

Room B

Room C

Figure 4.35: Third image shown to participants.

Figure 4.36: Third image shown to participants.

Figure 4..37: Third image shown to participants.

Figure 4.38: Fourth image shown to participants.

Figure 4.39: Fourth image shown to participants.

Figure 4.40: Fourth image shown to participants.

reddish colour, while the wall washers of the blue wall will be of a dark blue. Small LED strips will be added to the base of the plants, while the red sofa will have both a soft red light and a white light, both at an angle to be able to highlight both colour plus a possible person sitting down (figure 4.27).It is to be noted that RGB lighting was tested through ERCO's varychrome lighting, but the visualization proved that the addition of coloured filters to a warm white similar to tungsten was more successful for the test even though they transmit less light. Filters are also a better option in this case as the designer can pair up more precisely the colour of the material with the selection of a particular filter. All the filters used (blue for the blue walls, brownish red for the brick wall , pale red for the sofa, brown for the bookshelf and green for the plants) are unsaturated colours (pastel). All the white lights will have the same CCT of warm white (3000 K).
In all of the cases, the lights will be placed in a sort of grid system. The downlights used in figure B are 16 ERCO Quintessence Double Focus downlights, 16 W (1680 lumens), while the wallwashers in both figures A and B are 14 ERCO Quintessence lens wallwashers 16 W, a Parscan Spotlight of 12 W and a coloured ERCO Opton Spotlight of 12 W both directioned at the sofa. Addionatlly, linear LED strips (TALEXX module LLE G4 by Tridonic at 650 lm) will be placed in all of the slots of the book shelf and in the plants in rooms A and C, having a brown/red filter in the book shelves in room C. While the colour and the distributions of the luminaires will vary, the intensity will be maintained as a constant: lights won't be dimmed, except for the case of the linear lighting in the bookshelf, dimmed to a 20%, as it proved to be too bright in full power. In the wallwasher rooms, the lights will be at 0,7m from the wall.

The questions will be asked in a varied group of 7 people, the same sample as the test in the theater. The questions will be:

Which one do you find more inviting? Why?
Which one would you spend more than 3 hours working? Why?
Which one would you choose for relaxing? Why?
Which one would you chose for a dinner/party? Why?
Personal impression about the three rooms

It will be therefore be paying attention at the perception and mood people have with the addition of certain illuminations .

This test does not evaluate the best kind of luminaire used or how the colours are achieved., but aims to explore if the addition of colour plus a non-horizontal distribution generally causes more comfort and it's effective at the same time. The following views of the rooms will be showed in comparison with one another:

4. Results

In the first three image shown (figures 4.29, 4.30 & 4.31), where is possible to see all the elements of the room in one glimpse, all of the 7 participants chose room B for working and concentration, stating that it is perceived as generally more warm and softer than the others (even if the CCT is the same in all). 5 of 7 participants chose room B for relaxing too, stating the same warmth reasons; 2 participants said that room B was less confronting than the others. 3 participants said that room A was brighter, while 3 participants pointed room C as the darkest. However, 3 out of 7 participants chose room A to have fun/dinner party, while 2 chose room C.

In the second image (figures 4.32, 4.33 & 4.34), participants rated the image similary although this time there were no significant majorities. While 3 of them selected room A as the more inviting, other 3 did for room B. To the question of which one would they chose to study or work, room B and A got selected for the amount of light on the table, while room A was selected by 3 people to throw a dinner party, and other 3 selected room C. General comments still qualify room C as colder and darker at the same time, while room B in this case is generally perceived as darker.

In the third image shown (figures 4.35, 4.36 & 4.37), 5 people chose room A as the more inviting. For study or work, room B got chosen by the 7 participants as the table in this view is also perceived as the brightest of the tree. For relaxing, people chose mostly room A (5 out of 7) while the other 2 chose room C. For a dinner party, again, 6 out of 7 people chose room A for the combination of relaxing atmosphere plus visibility on the table.

In the fourth image shown (figures 4.38, 4.39 & 4.40), 3 out of 7 people chose room C as the most inviting, while 4 out of 7 chose room B. Still the winner for studying or working is room B. 3 out of 7 people chose room A for relaxing, while 4 out of 7 chose room C. As for the dinner party, the three where chosen almost equally, with room A getting chosen by 1 more participant in

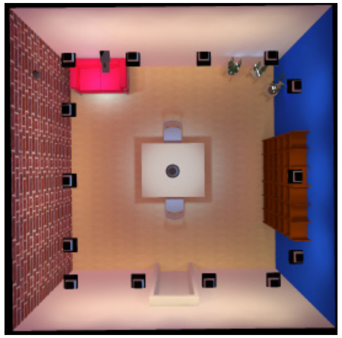


Figure 4.41: Top view of room A (wallwasher distribution)

Figure 4.42: Top view of room B (downlights distribution)

Figure 4.43: Top view of room C (wallwasher distribution + colours)

comparison to the others. The general thoughts were:
A - Inviting, warm, soft
B - Focused, sterile, intense
C - Cold, harsh, exciting

5. Conclusions

The illumination of the white wall in both room A and C was perceived as much colder, (and described consequently as less visually appealing) than the downlights in room B even though they were from exactly the same CCT at the downlights in room B. However, the walls are white and therefore reflect all of the wavelengths, while the floor, as it is made of wood, will reflect warmer colours, generating a general warmer tonality than in the other rooms (figure 4.42) ; in room A and C there is no light that points directly to the floor, creting a general impression of colder, harsher lights. Furthermore, the reflection factor of the white walls is significantly higher (88) than the on the floor and table (65 and 56), fact that would explain why they room feels “harsher” when the white wall is illuminated.
Whne first wall seen is the white one as it is in front of the viewer, it results in being more dominant in perception when seen than the others. This very same perception of warmth is what has made participants choose room B for the purpose of relaxing especially in the first views (figures 29, 30 & 31) . Interestingly, participants have also pointed out room C as the darkest, making the general use of colours in the room unsuitable for the perception of having enough light.
The photograph where room A gets chosen the most as the most inviting is when viewers are exposed to the lighting on the blue wall + the linear lighting in the bookshelves (figure 4.35). A combination of well defined elements including the brightness of the table seems to do the trick.

Similarly, room C gets chosen more as inviting in the fourth photograph, were is possible to see the brick wall. The coloured lighting makes the natural hue of the brick reflect throughout the room much more than in the other two light applications.

The reason why the table seems so different in lighting when the exact same fixture is used in the three rooms remains unknown, but affects entirely the reason why participants chose one room or another. It is theorized that the rest of the colours reflected from surfaces affect the perception of the central table piece, but it is undetermined exactly how.

A source of bias is drawn by this fact: seemingly the comparison of the three rooms to one another determine opinions that may have not been there when the participants would have seen the room in isolation: room C, for example, is perceived as too dark to study, but the lux on the table (approximately 750) are more than enough to that kind of applications (figure 4.44), as for normal office work only 500 lx are required, being possibly too much in room B (1700 lx) except if very detailed work would be taking place.
The problem of this test might have been than in either of the rooms was any selective lighting: while in rooms A and C

Activity	Illumination (lux, lumen/m²)
Public areas with dark surroundings	20 - 50
Simple orientation for short visits	50 - 100
Working areas where visual tasks are only occasionally performed	100 - 150
Warehouses, Homes, Theaters, Archives	150
Easy Office Work, Classes	250
Normal Office Work, PC Work, Study Library, Groceries, Show Rooms, Laboratories	500
Supermarkets, Mechanical Workshops, Office Landscapes	750
Normal Drawing Work, Detailed Mechanical Workshops, Operation Theatres	1,000
Detailed Drawing Work, Very Detailed Mechanical Works	1500 - 2000
Performance of visual tasks of low contrast and very small size for prolonged periods of time	2000 - 5000
Performance of very prolonged and exacting visual tasks	5000 - 10000
Performance of very special visual tasks of extremely low contrast and small size	10000 - 20000

Figure 4.44: Recommended lux level on workspace per activity

lighting is distributed accordingly to the different structures in the room, they were all lit, without taking particular advantage of any colour domination. The fact that the brick wall lit with red receives more acceptance in the participants in room C shows that it is not about lighting all the colours with coloured light, but about selecting which colours to light. Therefore, that the aim of using technology to identify the colour of particular elements result of automatization would probably not please the user.

This test depicts very obviously that lighting is about a the whole effect, and if colour is used, it has to be very well thought of and seeking a harmony amongst the other tonalities of the room, in both lighting and materials. Using colour according to the material might work if it is part of a whole illumination concept, and not automatically following the colours available in the room as theater might do sometimes.

Future work could include different types of rooms, preferably in real spaces that participants could walk into. Additively, to calcultate the MSRE (mean surface room exitane) to extract general conclusions of surface illuminated, beyond perceptions: “MRSE is a measure of inter-reflected light from surrounding room surfaces, excluding direct light from windows or luminaires.” Cuttle, (25).

DISCUSSIONS, CONCLUSIONS AND FUTURE WORK

1. On **what** to use in scene creation in interior lighting design

Conclusions have been drawn on the first test about the role of LED in theater: while the white coloured chip in the Source 4 still don’t deliver the same results as tungsten, it is satisfactory and can be used as a front light.
However,

What is the current state of white light LED´s in the architectural realm?

“LED’s challenge is now two things - power and warmths. LED need to perfect whites to get as much warmth as possible. (...) No one could dispute that the incandescent light (...) in inherently wasteful as a light source. What we like about it its is warm and yellow in tone, flattering for the human complexion, intimate and close to candlelight.” Chan (3)”

In terms of white quality centered around the human being (and that is, around its skin, in this case, of white and olive skin people) there have been also great improvements in making LED have the spectrum of tungsten, and as we have been able to witness, making it look quite similar too. In particular, some manufacturers like Xicato go further and no longer have tungsten as the only reference, (like in their Artist series in which they deliver a product very close to the tungsten reference illuminant) (figure 5.1) but try to create the perfect light basing their criteria in the opinion of how people perceive their skin under it. (figure 5.2)
“(...) with its Artists and Beauty Series, in which they developed fixtures specifically aimed at how skin looked. Together with Nulty+ lighting studio in London, Xicato carried out an experiment aimed at finding out which luminaire was better for make up testing on the skin.
“So often, as lighting designers, we are looking for lighting that enhances the beauty of materials or objects, such as wood, brick, jewelry or tomatoes,” said Claire Hamill, lighting designer at Nulty+ . “This is the first time we have looked at people as our primary subject. Accurate and flattering rendering of skin tones is a difficult challenge, because skin is such a rich and complex palette, consisting of many subtle shades. Our studies show that people feel

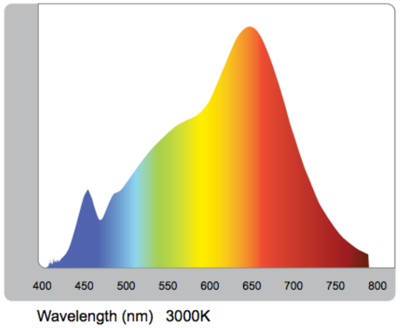


Figure 5.1: SPD of Xicato Artist series

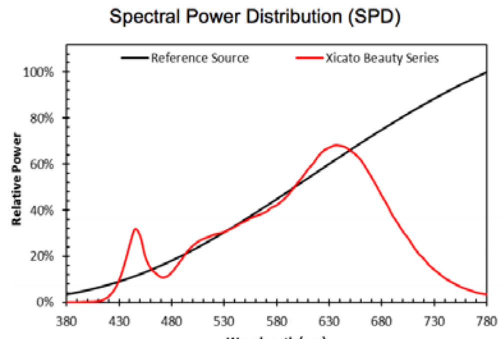


Figure 5.2: SPD of Xicato Beauty series

good when they look good, and Beauty Series does this while also providing the clarity and enhanced contrast that facilitates color matching.”

“The Beauty Series of LED modules was developed to support a collaborative study between University College London, Nulty+, Xicato, and a leading global cosmetics brand. In the results, “twice as many people in the study reported that their skin looked good, and that they felt good, under Beauty Series light, and 15% more people reported that foundation matched and appealed to their skin.
Managers and customers in cosmetics stores in which Beauty Series is installed have commented on how soft and natural the light feels. (...)
Xicato Beauty Series was developed over the course of the study to produce the best balance between beautiful, natural skin tones and color discrimination.” (32)

What can be extracted from this technology development is the fact that we find ourselves in a moment where manufacturers have the ability to tweak LED´s to very high levels of perfection, in which they are able to select precisely the exact wavelengths that will potentiate the look of something. In that aspect, and having confidence in a constant evolution, LED (without considering other aspects like colour of the chips through time etc) is winning territory and it won´t be long until we find it substituting other types of fixtures.

What about colour in architectural LED’s?

The colour spectrum test in the theater made it clear: RGB seems not enough to pursue all the possible colours that a designer may want to offer. Even in whites, the addition of extra colour chips would increase the quality.

“RGB is more than sufficient for many applications; however, some uses require far more spectral components. Many of ETC’s products happen to use seven colours of LEDs, because this approach gives the fixtures a much broader gamut of saturated colour as well as white light and soft pastels that much more closely mimic the spectral content of tungsten, with and without gels. This seven-colour system also combines the various emitters in very specific ratios, because not all colours of LEDs are of comparable brightness.
Very few LED luminaires take this approach to colour mixing. Additive colour mixing is an entirely different way of thinking than the subtractive method used with filters on tungsten, and it can be rather non-intuitive, especially when dealing with more than three primary colours. It takes a very good control system – one that knows the specific colour capabilities of a given LED fixture – to make the job of additive mixing quick and simple.” Gerlach (7).

Yes, the Source 4 dealt with colours remarkably. However, how applicable is this to architectural modules?

“While there are some LEDs with a white chip and three colour chips in one housing, those usually tend not to address a better colour rendering but to have a higher luminous flux at white light.So the question with some additional words is:

Why are there no multichip LEDs (5 or more chips) for the production of light with higher colour rendering?”

Apparently it is rather difficult to select a couple of dies for a single purpose. The more problematic is constructing an “universal” 6 or 7-die housing without making it unusable or too expensive for 70% of all possible customers - let alone the thermal problems you run into accumulating so many electrically independent components into one housing. “

Why is it not possible to find the most useful combination of chips to put them into a common housing?

The degree of freedom grows exponentially with an increasing number of LEDs. For each chip you add you have to select a binning with a dominant wavelength and a flux binning. Furthermore there are a bunch of other parameters associated with each die to select for a common housing many of which are temperature dependent.” Graham, (33).

Therefore, the idea of increasing the number of coloured chips in one LED housing seems complex and costly for the creation of specific architectural based modules, being the probable reason why it seems too much work for manufacturers to create such luminaire for interior design.

Possible solutions:

A. It seems that the application of these wide range of colours made in theater has to be obtained in architecture in a reduced way, that is, not intending to have all of the colours in one fixture but select some particular wavelengths to put into the same housing. For example, an intermediate solution sometimes used by larger architectural products to obtain high quality colours and reduce costs would be to custom design an LED or module for a specific application, like AWR (amber white red), which provides a wide range of saturated and unsaturated colours in the orange/red tones.

Future work could imply developing these kind fixtures and experimenting which chips could be paired together to achieve luminaires with broader gamut of colour.

B. What would the solution be, however, when those particular fixtures explained are not available and a very particular colour is wanted that normal RGB cannot achieve?

The proposed intermediari approach are filters. Having proved that RGB is, in its very best, hard to predict, it is necessary to take a step back and consider what makes colour in tungsten so good. The main reason is the enormous amount of filters available in saturated and unsaturated tones (in figure 5.3 one can see just a small sample of the wide variety of skin tones in LEE filters), very easy to install and not so easy to achieve, for what is seen, with RGB. The main problem filters had before was the heat generated by the tungsten, that destroyed them quite fast and made it necessary to pursue new ones:

Plastic colour filters (...) haven't found huge popularity in mainstream architectural application because they don't last for ages.. They (...) fade or blacken after a while if they are used in really close proximity to the lamp (...). On the up side, there is a great, and expanding, collection of colours in the theatrical ranges. Some filter swatch books have 200 plus colours from which to choose. (...) A long time ago, one of the pioneers of architectural lighting consulting, Tony Corbett who was used to using colour in the theater, and of course required a finer palette than red blue green and yellow, realised he needed a range of filters with some degree of subtlety, for his architectural applications. (...) Softone brand filters (*glass filters, very much used in architecture currently*) are still on the market .
Theatrical gels are cheap, have great colours, but don't last too long. Solid glass filters are cheapish, are available in a pretty good range of colours, some of the colours are a bit dull, but they do produce even colour across the width of the beam. Dichroic colours are crisp, extensive in range, expensive in price, efficient in transmission but prone to colour variation across the beam width. Thompson (24).

However, with LED´s, all the heat is generated at the back of the fixture, making it possible to take advantage of the wide variety of filters without fearing the degradation. It is true that the output is hard to expect depending on the type of white delivered by the LED source (as especially theatrical filters like LEE or Rosco are manufactured having the SPD of tungsten in mind), but even LEE filters developed a few years ago especial colour filters for cold white LED´s that would pair up to the same colours given by a tungsten, recognizing the need in the market for a filter system for LED's. (figure 5.4)

It is without doubt more easy to know what to expect from a white LED with a similar SPD to tungsten like some Xicato products. While the use of filters

Figure 5.3: Sample of skin tone variety in LEE filters

Figure 5.4: Sample of LEE's CL series for Cool LED filters

seems quite non-viable for linear lighting for installation reasons, in modular LED they could be very easily installed.

"I use (filters) all the time. Even if you have a hunch about what's the right way of doing something, or which are the right filters to use, until you actually come to do the focusing you can't really tell.Every time it's slightly different. Its to do with the chemistry, if you will, of all the materials around you: if they're reflecting light or not reflecting light." Chan (3).

Future work should investigate the look of different low, medium and high range in LED with different kinds of filters and establish therefore some general guidelines for use.

2. On **how** to approach scene creation in interior lighting design

This paper has very much been based in the emphasis of elements through colour and distribution in lighting, trying to establish a design criteria at the time of selecting luminaires for an interior space. This topic has been approached solely on the individual consideration of the objects placed in a room, and the results have proven to not be particularly satisfactory as in seen in the colour distribution test.

However, as already seen in many existing architectural applications, this does not mean that the use of colour in interiors should be dismissed. There are other many factors in lighting that could be considered and explored in future work when a design is approached:

1. The psychological effect of colours: in the test performed, surfaces that were perceived to have colder temperatures produced less pleasantness. In future work different rooms should be shown to participants with different colour dominances to investigate how do they feel about them.

2. Different colour contrasting criteria, like the colour contrast theory by Johannes Itten in which he defines contrast by hue, by value, by temperature,-contrast by complements, simultaneous contrast, contrast by saturation, and contrast by extension. Burton, page 37 (34). In figure 5.5 (bathroom in an unknown restaurant in New york) a contrast in hue using complementary colours is applied, adding by the means of distribution a new layer to the white material of the walls. While it does not have any visible conceptual approach, the sole contrasting nature of the two colours placed together work, creating a vibrancy in the view; this approach is very much used by luminic art installations like shown on the Introduction.

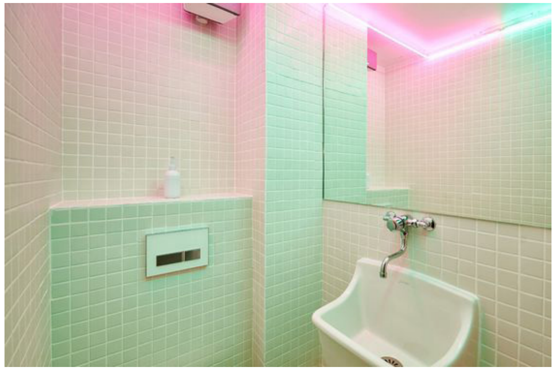


Figure 5.5: Unknown bathroom in NY

That is, concerning the colour of light. However, as we know (and have been able to further confirm in the test) designers will be faced with the challenge of lighting objects that will reflect different wavelengths. Furthermore, those reflections will have to be taken into consideration carefully to create a whole atmosphere. It can be concluded that while lighting independently might have good results, the whole cannot be forgotten and that individual object has to respond to a wider coordination.

Therefore, the background in architecture cannot be systematically treated as the background in theater, but uniquely when makes sense conceptually and visually.
It is also important to take into consideration the action that is taking place in the space, as that seems to affect the level of flexibility in blending the action space and the background together.
About the virtual "main action" area, thought of to respond and host many kinds of activities by the use of high quality white light has proven to be more successful, as the participants in the test many times chose the room in which that assigned area had more light intensity. However, again responding to the light design as a whole, future work should include the possible use of subtle colour addition on human based interactions as well to perpetuate the idea of an whole atmosphere, including, this time, the actors.

In a test about colour preference in merchandising made for Xicato, two relevant conclusions were drawn:
"Light effects can be used to help specific products stand out and make a statement. (...)
However colour enhancement is clearly not for all applications. For some participants, and in some applications,more vibrant colours appear too strong and are perceived as being too artificial.Whether or not colour enhancement by lighting is appreciated depends on the merchandize targeted, type of store and the message that it wants to radiate." C. Knight, page 5 (35).

(...) as a rule we know what colours things are. And that means, in particular terms, that changes in the colours of individual objects are largely eliminated in everyday life. This fact (...) is a perceptual effect in its own right; (...) our perception is not merely passive but actually normative and functional. Thus corrections are made during the process of perception, that seek (...) constancy in things and thus constancy in colour as well.
We ordinarily do not see the coloration of an illumination on an individual object (..) instead, we see the colouration of the illumination as a tinting of the whole (...) a totality effect. (...) it is the emotional tint of the space in which one finds oneself that determines how one feels.
Through coloured illumination (...) all of what is seen takes on a tint that turns the diversity of what is seen into a unified whole. (...) Therefore, it is appropriate to say that illuminations are perceived as atmospheres."
Bachmann, (7)

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