Psychophysical Evaluations of Modulated Color Rendering for Energy Performance of LED-based Architectural Lighting

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ABSTRACT BY MARIA DO ROSÁRIO THOMPSON

Submitted to the Department of Architecture on January 12th, 2007, in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the field of Architecture: Design & Computation, at the Massachusetts Institute of Technology.

This thesis is focused on the visual perception evaluation of colors within an environment of a highly automated lighting control strategy. Digitally controlled lighting systems equipped with light emitting diodes, LEDs, can produce a range of different qualities of light, adjustable to users' requirements. In this context of unparalleled controllability, a novel energy-saving lighting control concept inspired this research: strategic control of Red, Yellow, Green & Blue LEDs forming white light can further increase energy efficiency. The resulting (more efficient) white light, however, would have decreased "color rendering" (i.e. the ability of accurately reproduce the colors of illuminated objects). The notable point is that while color rendering is necessarily affected, the appearance and light levels of the white light can stay the same. But how objects' distorted colors are perceived within a real life architectural context is a key, ensuing question. This research investigated the hypothesis that a significant range of color distortions would be unnoticeable under a dynamically controlled LED system, when operating outside of users' main field of view. If successful, such control technique could minimize peak hours lighting energy waste, and potentially enable up to 25% of power reduction.

Three incremental series of psychophysical experiments were performed based on subjective assessment of color changes under continuously modulated color rendering from white LEDs. Visual tests were carried out for central and peripheral vision on a full scale mockup of an architectural scenario. Results confirmed the fundamental hypothesis, showing that the majority of subjects did not detect the color changes in their periphery while the same color changes were noticeable with direct observation. The conclusion chapter provides fundamental guidelines for how to extrapolate the experimental results into real life and apply the data to architectural settings. Hypothetical architectural scenarios are presented and the potential for energy savings is discussed.

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To Charles and Samuel

The city does not need the sun or the moon to shine on it, for the
glory of God gives it light, and the Lamb is its lamp.

Revelations 21:23

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CHAPTER 1. INTRODUCTION

1.1. BRIEF DESCRIPTION

Implementation of solid state lighting technology, more specifically light emitting diode, LED, systems, is expected to establish a new paradigm in architectural illumination. In addition to impressive energy saving promises, LED-based sources offer what was inconceivable with conventional sources: controllability of the spectral, spatial, and temporal properties of light (Navigant Consulting, Inc., 2006). In this context of unprecedented controllability a provocative concept inspired this research: strategic control of Red, Yellow, Green & Blue LEDs forming white light, can further increase efficiency because of the way our eyes sense the different colors. Higher luminous efficacy of LED white light can be attainable if its mixture favors those colors to which our eyes are most sensitive. The notable point is that while the individual color channels are modulated, the appearance and light levels of the white light can stay the same. But, how the colors of objects and spaces are rendered under such a changing light is a key, ensuing question. The main goal of this thesis is to appraise the perception of color changes within an environment of a highly automated LED lighting control strategy. The main hypothesis is that a significant range of color distortions will be negligible within certain architectural scenarios.

1.2. MOTIVATION

1.2.1. LED Technology May Be the Future of Lighting

The lighting industry and scientific community are experiencing a historic revolution with the development of new illumination sources based on solid state lighting technology, more specifically light emitting diodes, LEDs. According to the United States Department of Energy, DOE, "*no other lighting technology offers so much potential to save energy and enhance the quality of building environments*" (Navigant Consulting, Inc., 2006). Systems based on LEDs have the potential to substitute conventional lighting sources such as incandescent lamps and fluorescent tubes for general illumination applications, and major economic and environmental impacts can be realized (Kendall & Sholand, 2001). There are three main aspects of LED lighting technology that can potentially make it a disruptive technology for architectural lighting: (1) performance (i.e. energy efficiency, life span, thermal properties); (2) controllability, and (3) physical form factors (i.e. compactness, ruggedness, optical structures).

1.2.2. Great Savings Potential

The DOE has optimistic predictions for energy saving potential of Solid State Lighting technologies (more than $120 billion in electricity bill savings for the United States from 2005 to 2025). Tables 1 and 2 show the encouraging numbers particularly applied for LED lighting technologies.

1.2.3. LED Architectural Lighting: A Great Opportunity

Controllability will be the strongest driver of adoption for LED technology in architectural lighting together with energy efficiency. The great opportunity comes from the fact that one day grids of these tiny little lamps, in conjunction with digital controllers and sensor networks, could bring light only *when*, *where*, and *how* it is desired. Such lighting will be able to adjust to users' requirements which could result in tremendous benefits for architectural lighting, not only in terms in aesthetics but also for building automation,

Light Source	Typical Luminous Efficacy Range in lm/W (varies depending on wattage and lamp type)	Lifetime
Incandescent	10-18	1,000 hrs
Linear fluorescent	50-100	10,000 hrs
Cool white LED 5000K	45-59*	20,000 hrs
Warm white LED 3300K	22-37*	20,000 hrs
Future white LEDs	up to 200	100,000 hrs

Table 1 - Comparison of Lighting Technologies. Data from US Dept. of Energy. *Current as of October 2006.

	2005	2006	2007	2008	2009	2010	2015	2020	2025
Efficacy (lm/watt)	47	56	66	76	88	99	142	158	162
Lamp Life (1000 hours)	16	19	23	28	36	45	87	98	100
Lamp Cost ($/klm)	146	127	107	86	67	51	11	4.3	3.3
Lighting markets Penetrated	Low-Flux	Low-Flux	Incand.	Incand	Incand	Incand	Fluor.	All	All

Table 2 - Performance targets for SSL-LEDs – OIDA Technology Roadmap, 2002.

communication, safety, and health purposes.

One of the main challenges for controlled LED lighting for architectural purposes is that most often light must be continuously perceived as *white*; and lighting effects must be *inconspicuous* to the users. Advanced controllability of white light includes, other than variation of light levels (i.e. dimming), the manipulation of its spectral composition. When a controller manipulates the spectrum of a white light source, it is essentially altering its main chromatic properties, which can be understood in two ways: properties that describe the *appearance of light* (contained in two attributes: *color temperature* & *brightness*); and properties which explain the *color appearance of objects* under such light (*color rendering*). The variation in color temperature implies variation in the "color" of the white light, (i.e. from yellowish to bluish white), which allows designers to create visually appealing architectural spaces (figure 1). Variation in color rendering is much less obvious but with equally important visual impact. The color rendering (CR) of a light source tells whether the innate colors of illuminated objects will likely be preserved or distorted (figure 2). When the colors of objects change, it is not immediately obvious to the viewer but it can disturb the entire visual experience within a space.

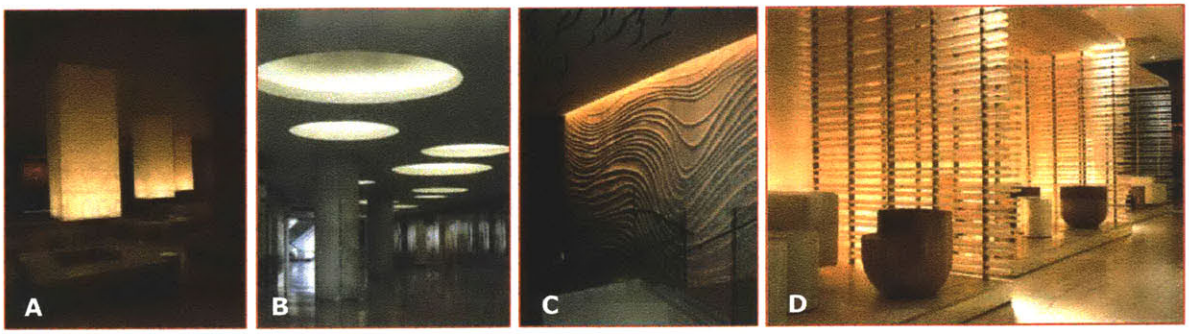

Figure 1 – Demonstration of visual effect of different color temperatures: (a), (c) & (d) show low color temperatures at the 'W Hotel', Times Square, New York (Lighting Design: L'Observatoire International, NY, Hervé Descottes & Maria Thompson); and (b) shows high color temperature at the 'Miami Heat Arena', Miami, (Lighting Design: L'Observatoire International, NY, Hervé Descottes & Stephanie Grosse-Brockoff).

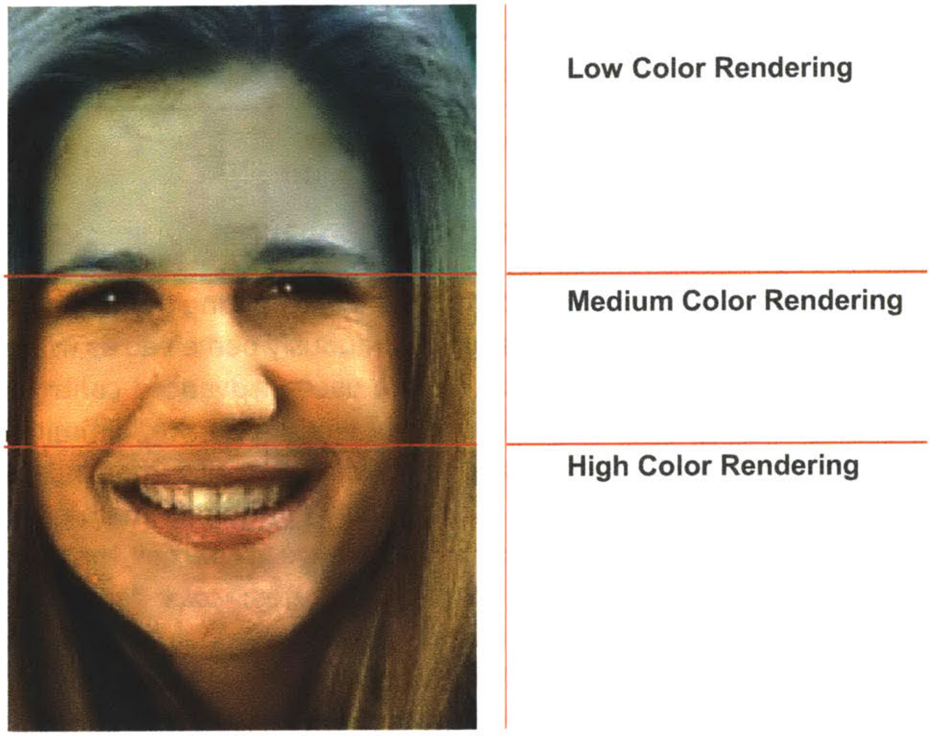

Figure 2 – Demonstration of visual effect of different color rendering on skin.

The notable point in color rendering modulation is that while changing color rendering, light levels and color temperature can stay constant and hence the appearance of the light stays the same. Only the appearances of objects would change, which can be made visually subtle, or possibly "invisible".

1.2.4. CR Modulation: a Grand Concept?

But why would we want to change color rendering? Automated control of Red, Yellow, Green & Blue LEDs forming white light could change the way objects' colors are rendered, in order to: (1) Enhance visual performance by tuning the color rendering to strategically boost certain colors within a room. For example, adding more red to a color-mixing white LED could make a ruby bracelet look more stunning in a jewelry display; or (2) Further expand the energy efficiency of a LED lighting system, because reducing color rendering increases luminous efficiency. Modulated color rendering can potentially enable a system that dynamically shifts from 'energy saving mode' (low color rendering)' to 'quality mode' (high color rendering) according to occupancy (figure 3). This technique is based a fundamental trade-off between color rendering and luminous efficacy. This trade-off occurs because human vision does not sense all colors of light in the same manner. Considering a cluster of many colored LEDs, and given the same power for each light, our eyes will sense greenish light to be brightest (see Chapter 2 for more details). Therefore, the high luminous efficacy of a color-mixing LED white light can be attainable if its spectral composition favors those colors to which our eyes are most sensitive to. This is why a white light with strong power in the yellow-

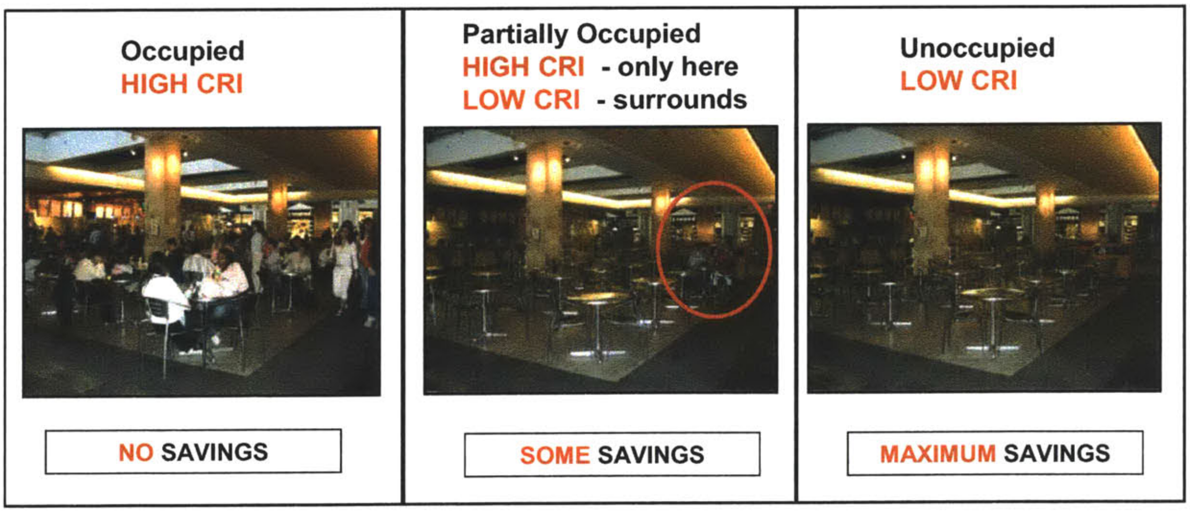

Figure 3 – Demonstration of color rendering modulation control strategy, as a possible implementation of color rendering modulation for energy savings.

green color will potentially attain superior luminous efficacy. By selecting the mixing of colors and adjusting their intensities individually, the spectrum of a white LED can be strategically designed for a variety of luminous efficacies.

The exercise of color mixing adjusting the spectrum of white light according to this fundamental energy-rendering trade-off constitutes the basis of this thesis research. It is inspired by one underlying architectural lighting idea: save energy by bringing empty areas to a reduced color rendering while keeping the same light level and color temperature. For example, when the area is unoccupied the color rendering (CR) can be reduced to its lowest power consumption keeping the same lit appearance, that is, the energy saving change could be 'invisible' to someone approaching the area or looking at it from afar. While dimming lights down is well understood as an effective method to save energy in unoccupied spaces, it has also been shown that it can be unacceptable for open-public spaces because darker areas appear uninviting or potentially unsafe. The ability to lower CR in marginally occupied spaces that would not otherwise tolerate dimming could potentially tackle a long standing energy savings challenge: lighting energy wasted in public spaces where large empty areas often need to remain *on* at full power during expensive peak hours. Such a technique if successful could allow peak time wattage decreases. A system employing the proposed trade-off-based control technique could achieve up to 23% power reduction (see chapter 6 for more details).

1.2.5. Tolerance Criteria: A Research Need

But, how colored surfaces and spaces are perceived under a light with changing color rendering is an unanswered question. When the prevailing lighting in a room transitions through different qualities of white, it can impact not only the spatial aesthetics, but also how effectively and efficiently people's eyes can process the visual information therein. The lighting community is therefore in need of investigations which properly explore and quantify the limits of this unprecedented level of flexibility in controlling the spectrum of white light. Color scientists and lighting engineers are searching for a numerical and qualitative description to the spectral qualities of LEDs; lamp manufacturers would like to plan their light sources to optimize performance indices using chromatic descriptions; and architects would like to receive guidelines for applying and controlling these (white but colorful) sources in practice.

Although no significant LED penetration in general illumination is expected to occur before some fundamental efficiency and cost breakthroughs are realized (Navigant Consulting, Inc., 2006), the lighting community has been dedicating tremendous efforts to investigate issues of practical implementation for LED systems. Color rendering has always been a hotly debated subject, and now it is receiving even greater scientific attention as a practical concern in lighting. For example, the field of color rendering, uniquely as it related to LEDs, is going to be considered at the quadrennial meeting of the International Commission on Illumination (CIE) in the summer of 2007, with specific invited talks, two paper sessions and a workshop completely devoted to color rendering. Likewise, many corporate, academic and governmental research institutions are devoting hard work to research color rendering in the context of LED lighting (Navigant Consulting, Inc., 2006).

1.3. Contribution

Psychophysical issues such as visual comfort, well-being, and aesthetic judgment, related to dynamic control of chromatic aspects of multi-chip LED white light, have not been addressed enough. It is overwhelmingly agreed (Davis & Ohno, 2005; Schanda, 2002) that color perception under multi-chip LED systems is of high importance, and that careful psychophysical experiments should be carried out to address how such issues should be handled. In this thesis, the visual perception of colors under illumination of changing color rendering was studied in the context of full scale realistic architectural conditions. Measurements of physical color changes on illuminated objects were compared to the results from visual tests, and are presented. Such experimental results and the succeeding analysis and conclusions constitute the core of this work. It is mainly addressed to researchers and designers interested in current research on LED systems, lighting controls, and color rendering; both in terms of architectural lighting, and in terms of psychophysical assessment of color perception.

Traditional lighting controllability is restricted to dimming lights up or down. In LED lighting, users and lighting professionals will make decision about how to control spectral mixture (all chromatic aspects of the white light) according with occupancy, daylight, or colors in the space. One of the goals of this thesis is also to provide valid useful information for the lighting community about LED controllability. In the conclusion chapter of this manuscript a demonstration will be given of how to extrapolate the experimental results into real life and apply the data to architectural scenarios. Hypothetical architectural scenarios will be presented where color rendering modulation occurs in response to occupation and activities in space and the potential for energy savings will be discussed.

At the time when fluorescent lamps were introduced, extensive research investigated perceptible color differences as well as the relationships between the spectral compositions of white light and its chromatic properties, including color rendering (Harington, 1954; Crawford, 1961; Pracejus, 1967; Aston & Bellchambers, 1969; Bellchambers & Godby, 1972; Boyce, 1977; DeLaney et al, 1978; Vrabel et al, 1998; Boyce & Cuttle, 1990). Typically, in these experiments color samples, pictures or objects were viewed within light boxes, or small rooms, and were presented to observers either side-by-side, or by sequential examinations. Only a few of these studies were conducted in full scale rooms using mockups of real life scenarios during the investigations (Pracejus, 1967; Bellchambers & Godby, 1972). Just very recently similar visual studies started to be conducted for LED lighting investigations (Stanikunas et al, 2004; Bodrogi et al, 2005; Sándor & Schanda, 2006). All of the LED based psychophysical assessments so far used light boxes similar to those used in the past, whereby assessments are made of the appearance of color samples. In real life, however, changes in color appearance are to be detected in much more complex scenarios and by memory, not by simultaneous examinations. Therefore, it seems logical to tackle the color rendering case by experimental determinations of perceptible change under simulated reality. This is what was done in this work, and it is the first known psychophysical investigation on LED lighting in the context of realistic architectural conditions.

Results were derived from three incremental experimental phases, and also from a detailed survey in lighting and LED research. Experimental Phase 1 (1A and 1B) was conducted in laboratory conditions and results were used as baseline for Phase 2 when the full scale tests were conducted. All visual tests were based on subjective ratings of color changes under modulated color rendering. It is important to point out that only one specific color rendering control strategy (modulation of the ratio of red to yellow LED emissions in search of higher luminous efficacy) was investigated with respect to one spatial scenario (containing prominent red components). Therefore the results specifically inform about visual perception under such circumstances in terms of visual acceptability of the following color distortion correlates: (a) Colors within the room (prominent saturated red); (b) Field of view (10° and 20°); (2) Automated continuous CR modulation (eleven LED white spectra of different CR sequencing within one minute).

The results and recommendations drawn from this research work were: (1) Measurements of color-perception differences under tested LED composite white spectra of different color rendering; (2) Determination of visual tolerances to reduced color rendering in adjacent areas from viewer's position (10° and 20° eccentricities); (3) Measurement of correlation between reduced CRI and visual perception of various colors of high and low saturation; (4) Validation of the assertion that color rendering rebalancing (via RYGB variation) will potentially be able to be finely controlled to match environmental features (i.e. surface colors, space activities and daylight component).

1.4. RESEARCH QUESTION & HYPOTHESIS

The main goal of my visual experiments was to appraise the perception of changes in color rendering when these happen in people's surroundings, and verify the hypothesis that a significant range of such generated color distortions would be invisible under realistic viewing conditions. The ultimate intent is to provide psychophysical evidence to support the previously described energy saving control strategy whereby color rendering would be "invisibly" reduced in unoccupied surrounding areas, allowing savings without lowering light levels.

My experiments primarily sought answers to the following questions:

- Can dynamic modulation of color rendering be invisible?
- If such color rendering changes are visible with direct observation, would they be unnoticeable in people's surroundings?
- How much can we reduce the color rendering of the LED illuminants before people notice a change in appearance of the scene within 0°, 10°, and 20° fields of view?

1.5. METHODOLOGY & ROADMAP FOR EXPERIMENTS

Three incremental phases of psychophysical experiments were conducted where human subjects evaluated a sequence of white composite spectra generated by a multi-chip LED system (equipped with individually tuned Red, Yellow, Green and Blue LEDs) in comparison with a reference source (incandescent). The color temperature and illuminance of all light sources were held constant, while each of the LED spectra had a different color rendering. In each experiment, physical measurements were collected from the illuminants (colorimetric color differences, ΔE*, color rendering Indices, CRIs, and other values) which were compared to the psychophysical results. In the first two experimental phases (Phases 1A & 1B) subjects' direct observation comparisons were solicited for the visual apperance of twenty four color samples of various hues and saturations. In Phase 1A the two different viewing booths were seen simultaneously (side-by-side); and in Phase 1B the booths were seen sequentially, with booths located in opposite sides of the room.

In Phase 2 the visual tests were performed in a full scale mockup where subjects looked from three different angles at two identical dining areas positioned side-by-side under incandescent (fixed lighting) and LED illumination (changing lighting with different CRI). The intent of Phase 2 experiments was to determine the degree of variation from an "ideal" color rendering (incandescent) which could be tolerated by the observers from peripheral angles (10° and 20° tests) in comparison with what they would detect with direct observation (0° foveal tests). The criterion used was a *just noticeable difference* from the standard when judged by memory only. The test field was seen first under "ideal" conditions of color rendering (incandescent illumination of color temperature 3000K and illuminance 270 lux). By reducing a proportion of the red radiation from the white LED mixture and increasing a proportion of the yellow radiation, it was possible to transform the quality of the illumination to greatly inferior color rendering but of equal appearance. By making the rate of change sufficiently slow, the observers' states of adaptation followed the change and were unaware of the kinetics of the system.

The question was then whether the observers would ever notice the changes; and if they did, at which point during the section would they detect the color changes. This moment varies from observer to observer and also depends upon what she/he is looking at within the entire scene. Therefore a fairly large number of observers had to be tested looking at a variety of test objects in order to arrive at a statistically acceptable result. Forty observers took part in the experiment.

1.6. THESIS ROADMAP

This thesis is organized in seven chapters. After the introductory chapter 1, chapter 2 contains a fairly broad description of the basic knowledge of photometry and colorimetry that is needed for the comprehension of the thesis. Chapter 2 can be regarded as a "technical section", and it is directed to readers who need background information on the specific aspects of color, vision and light science. It starts with a description of the distinction of radiometry, photometry and colorimetry, and how each plays a role in the reading of this thesis. An overview of the fundamental knowledge of color vision and a brief physiological description are given, mainly focused on making the reader aware of how the human visual system sensitivity to light is complex and nonlinear. The use of the differentiated eye sensitivity is then explained as part of the integrated system of photometry and colorimetry developed by the International Commission on Illumination (CIE) in 1931. The next sections in Chapter 2 provide information on light science. Conventions used to describe light phenomena will be described, such as spectral power distribution (SPD) of light sources, spectral reflectance of an object, CIE chromaticity diagrams and coordinates; and properties used to explain spectral quality of light sources, such as color temperature, brightness and color rendering.

Chapter 3 presents an overview of the research work done in lighting during the early days of fluorescent technology from 1950s through late 1960s, which was dominated by a long search for a better understanding of the relationship between lamp spectrum and human visual perception. When fluorescent lamps were introduced, in early 1940s, this interest further expanded due to the fact that this technology enabled the manipulation of white light's spectral components. The lighting community today working with LED technology is facing very similar challenges to that time when color mixing strategies done with phosphors were studied for higher efficiency and better color rendering.

Chapter 4 contains an introduction on LED technology, as well as a description of the most relevant recent work exploring color rendering issues starting on early 1990s. The related research described in both Chapters 3 and 4 mainly refers to qualitative and quantitative assessments of color involving psychophysical methods of visual comparison between two light sources of different color properties: a narrow-band test source (i.e. fluorescents, or LEDs), and a full-spectrum reference source. These experimental works were conducted at photopic[1] levels typical of interior lighting and used various techniques to investigate spectral quality of artificial lighting.

Chapters 5 and 6 contain the description, analysis and conclusions of the three incremental sets of psychophysical experiments based on subjective ratings of color changes under modulated color rendering. Chapter 5 is dedicated to Phase 1 (A and B), where experiments were performed using a double booth set up. Chapter 6 is dedicated to the detailed description of experimental phase 2 where the visual tests were performed in a full scale mockup simulating a real life scenario.

Chapter 7 contains the conclusions from the thesis research, related work and experimental results. It also provides fundamental guidelines for how to extrapolate the experimental results into real life and apply the data to architectural settings. Hypothetical architectural scenarios are presented and the potential for energy savings is discussed.

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[1] Photopic vision corresponds to vision under well-lit conditions (luminance level 1 to 10^6 cd/m^2). Photopic vision allows color perception.and is the scientific term for human color vision under normal lighting conditions during the day. Mesopic vision is a combination of photopic and scotopic vision in low but not quite dark lighting situations (luminance level 10^{-2} to 1 cd/m^2). Scotopic vision corresponds to vision in dim light (luminance levels of 10^{-2} to 10^{-6} cd/m^2).

CHAPTER 2. TECHNICAL BACKGROUND

2.1. RADIOMETRY, PHOTOMETRY, COLORIMETRY

Light is radiant energy. Electromagnetic radiation transports energy through space and its portion which is visible to the human eye is in called visible light. Visible light, as well as other types of electromagnetic energy, is measured and described by its wavelength in nanometers. Color is the sensation that is produced when the eye responds to visible light (Figure 3), and a typical human eye will respond to wavelengths from about 380 to 780 nm (Evans, 1965). A broadband source, like the Sun, emits the energy throughout most of the spectrum, while single-wavelength laser emits radiation only at one specific wavelength.

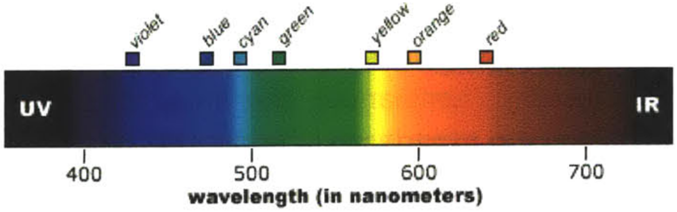


Figure 3 - When we see color, we see electromagnetic radiation with wavelengths between about 380 to 780 nm. In fact, each wavelength has its own color in the visible spectrum which makes it unique. The colors can be described as follows: Violet <450 nm, Blue 450-480 nm, Cyan 480-500, Green 500-530 nm, Yellow/Green 530-575, Yellow 575-585 nm, Orange 585-610, and Red >610 nm.

Radiometry is the science of measuring electromagnetic radiation in any portion of the spectrum. These are pure physical representation where the lighting quantities are measured just like any other physical quantity without subjective limits. But the perception of light and color are partially subjective phenomena, and visible light is typically measured by the techniques of photometry which is the science of measuring visible light in units that are weighted according to the spectral sensitivity of the human eye. Colorimetry is the science that quantitatively describes color, and creates standards by which to measure color, using mathematical techniques and software to ensure fidelity across media, allow accurate color mixing, and to develop color optimization (Judd & Wyszecki, 1975; Wyszecki & Stiles, 1982).

The measurement of 'how much light' can be made objectively with the photometer and subjectively with the human visual system. It is not hard to measure the amount of light reflected off an object. This is exactly what physicists do. But psychologists, neurobiologists, color scientists, artists and lighting designers are interested in human response to light. There are confusions among those not too familiar with photometry and colorimetry, concerning the distinction between luminance and brightness. Luminance is the "how much" based on radiant power (watts) evaluated by the human eye spectral sensitivity. Brightness is the subjective sensation stimulated by luminance (influenced by all luminances in the field of view), and can be described as how the human visual system responds to light; or how bright the average human eye judges a light to be independent of color appearance (Stiles, 1954; Judd, 1958). Brightness is measured by asking human subjects to match some reference brightness. Such experiments are called "color matching" and have been vastly used in investigations of light and color (Stiles, 1959; Schanda et al, 2002).

Although it is natural to imagine that sensations of brightness are direct representations of photometric intensity (luminance), the amount of light returned to the eye from an object and the experience of brightness it creates are related only indirectly in a way that is not yet understood (Lotto & Purves, 1999; Lotto & Purves, 2003).

A model of perception of color has been proposed which says that perception of color can be coded by three principal color receptors (Young, 1802; Boynton, 1979; Boynton, 1996). This model defends that nearly every colored light can be matched with no more than three lights, called primaries, in various combinations. This model underlies the system of colorimetry used today. Although colorimetry is based upon human perception, its strength and long-standing utility are based upon its simplicity for characterizing the color (in the physical sense) of visible radiation while still providing a useful approximation of color (in the psychological sense) appearance. Remarkably, the integrated system of photometry and colorimetry standardized by the International Commission on Illumination (CIE) in 1931, is almost universally used today (Le Grand, 1968; Wyszecki & Stiles, 1982).

2.2. COLOR VISION

Color vision processing in our system is initiated by absorption of light by three different types of photoreceptor cells, called cones. The three classes of cones have different but overlapping spectral sensitivities accounting for vision of short (S), middle (M), and long (L) wavelengths (Boynton, 1979; Dartnall, Bowmaker and Mollon, 1983) (figure 4). The spectral sensitivity of S-cones peak at approximately 420 nm (evoking a sensation of blue color); the M-cones peak at 530 nm (evoking a sensation of green color); and L-cones peak at 560 nm (evoking a sensation of red color). Color vision is therefore described as trichromatic, and initial psychophysical studies by various scientists using color-matching experiments demonstrated that colors could be matched by the use of three different primaries.

Figure 5 shows the universally used CIE data for the color matching functions of the average human eye. These are in idealized form, expressed as three spectral functions of wavelength, x, y, and z. These three functions are a transform of experimental color matching data using real primaries such that y contains all the luminosity, while x and z contain no luminosity, but are only color. It should be noted that the y curve is actually the V(λ) function (figure 6) which demonstrate the human's eye differentiated sensitivity to the brightness from each wavelength (see next section for explanation of the V(λ) function). Each function is used to weight the spectral power of a test light source to determine the amount of an imaginary primary light source. These three imaginary primary sources when mixed together will match the original light source. This forms the basis of the CIE system of colorimetry.

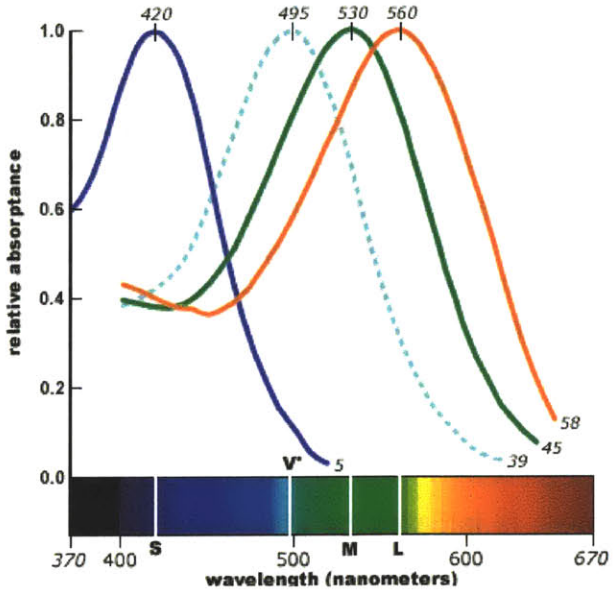


Figure 4 - Normalized spectral cone sensitivities for Short, Medium and Long wavelengths(human photopigment absorption curves). Data from Dartnall, Bowmaker & Mollon (1983).Figure from http://www.handprint.com/HP/WCL/color1.html.

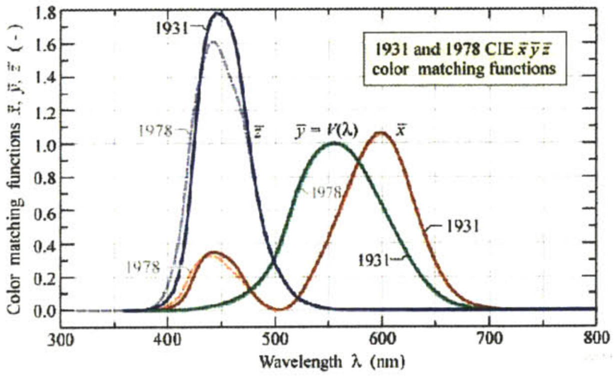


Figure 5 - CIE color matching functions. Note that the y is identical to the eye sensitivity function V (λ), (figure 6). The CIE 1931 CMF is the currently valid official standard. Data and figure from www.LightEmittingDiodes.org.

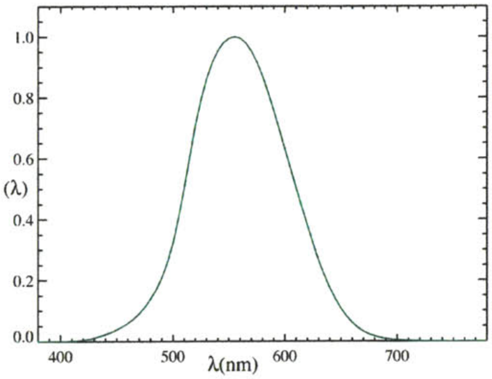


Figure 6 - Photopic V(λ) function, which defines the spectral sensitivity of the visual system in current photometric practice. Figure from http://en.wikipedia.org/wiki/Photopic_vision.

The trichromatic nature of color vision will enable almost any color to be matched by a mixture of three colors. This trichromacy of vision is also approximately linear. This means that colorimetric equations have properties of ordinary linear equations. Tristimulus values represent the quantities of each of the three imaginary primaries necessary to achieve a match for color and luminosity.

2.3. THE USE OF V([LAMBDA]) AS THE BASIS OF PHOTOMETRY

As different parts of our eyes are sensitive to different types of electromagnetic radiation, the human visual system response to light is complex. It varies not only with wavelength (each wavelength excites the Short, Medium and Long wavelength cones in different ratios, and is perceived as a different color), but also with the amount of radiant flux (our perception to these colored light varies if we are in dim conditions), whether the light is within our main focal area or in the periphery, and also depends on the spatial complexity of the scene, the adaptation of the eye, the psychological and physiological state of the observer, and many other variables. The CIE defines the relative response of the normal human eye to monochromatic light at the different spectral frequencies, for well-illuminated conditions (photopic vision). This spectral response is denoted as V(λ) (V[lambda]) which is a nominal average (derived from a series of psycho-physical experiments) of the human visual response to light (Boynton, 1979; Le Grand, 1968).

V(λ) indicates that the human visual response peaks at about 555 nm (yellow/green region) and decreases to zero in the ultraviolet (UV) and the infrared (IR) wavelength regions (figure 6). Therefore, given the same output of power at each wavelength region, our eyes will sense the greenish light to be brighter. This is why, among equally efficient light sources, a white light source that has a large fraction of its power in the yellow-green area will have the highest visual efficacy, i.e., the highest lumens per watt. However, without a reasonable proportion of red or blue in its output, a light source will not be able to render colors satisfactorily. The CIE V(λ) weighting was originally chosen because it yields a precise and repeatable visual response, but it has limitations since this model represents the 'standard perception' of light of a 'standard observer' under carefully controlled conditions.

The CIE has standardized supplements to of the V(λ) function realizing that the CIE 1931 colorimetric system, which is based on a 2° foveal observer, does not cover all the possible visual conditions (Boynton, 1979; Boynton, 1996; Schanda et al, 2002). Modified V(λ) functions were designed. For example, because the V(λ) luminosity function is based on a high light level, (photopic response, with luminance level 10^6 cd/m^2), this will not accurately indicate the visual response in dim lighting conditions, and different response functions were established for the spectral luminous efficiency for lesser illuminations (Sharpe, Stockman and Jagla, 2005). They are called mesopic vision for intermediate levels of illumination (luminance level 10^-2 cd/m²) and scotopic vision for very low levels of illumination (luminance levels of 10^-2 to 10^-6 cd/m²). As a result, a second photometric system is used for scotopic vision, the V'(λ), with a maximum near 505 nm (figure 7). In addition several further ones are in use in light and lighting. The most important of these is a *V*10(λ)-function function (Stiles & Burch, 1958), based on the 10° foveal observer, which is widely used when large visual fields are evaluated (Morren, 1979; Rea, 1999).

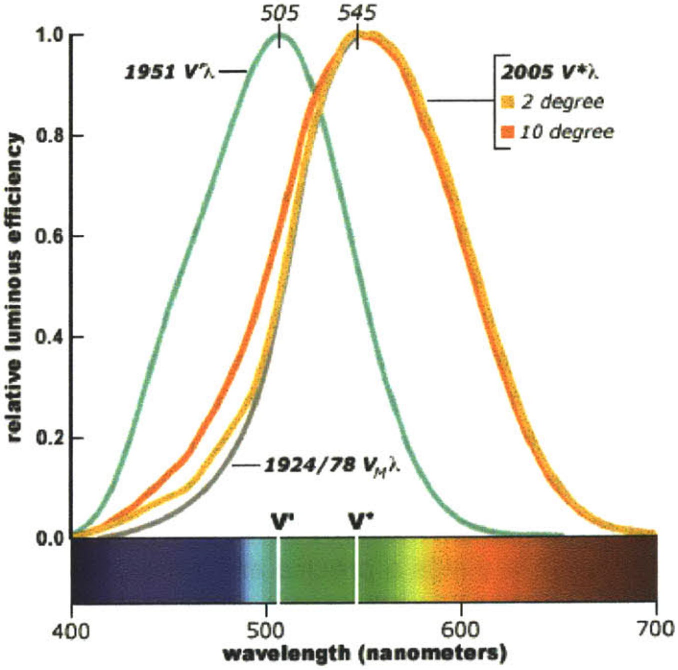


Figure 7 - Photopic & scoptopic luminosity functions. Photopic functions based on the 2° and 10° quantal cone fundamentals of Sharpe, Stockman, Jagla & Jägle (2005), shown with the CIE 1951 scotopic function and the 1978 photopic function; all curves normalized to equal peak sensitivity on a linear vertical scale. Figure from http://www.handprint.com/HP/WCL/color1.html.

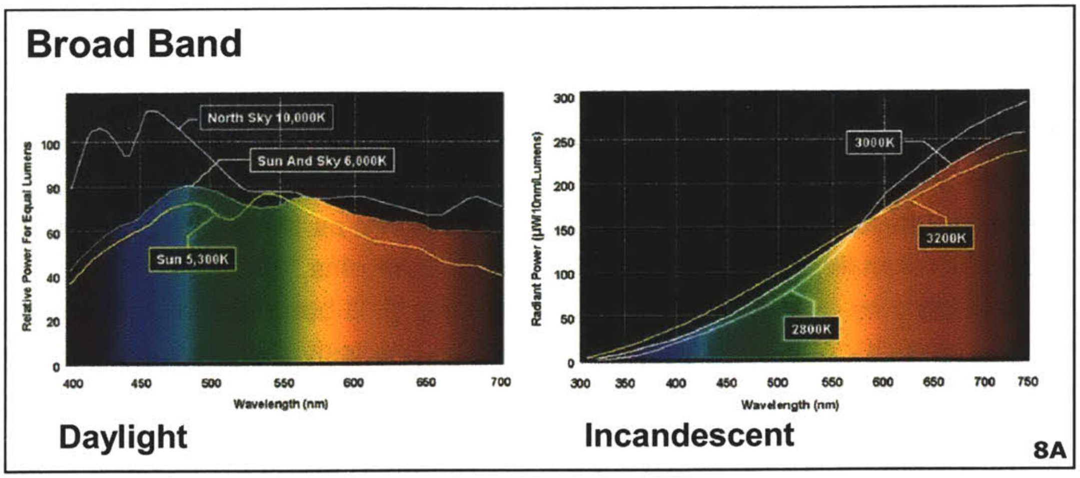
2.4. SPECTRAL POWER DISTRIBUTION (SPD)

The Spectral Power Distribution (SPD) Curve is the most complete description of a light source color characteristics provided by a detailed plot of power emitted in the different regions of the spectrum. Such a plot contains all the basic physical data about the light and serves as the starting point for quantitative analyses of color (Williamson & Cummins, 1983). The SPD can be measured by a spectroradiometer. From the SPD both the luminance and the chromaticity of a color may be derived to precisely describe the color in the CIE system.

Figure 8 shows a typical spectral power distribution graph for daylight along with SPDs for incandescent, fluorescent and mercury lamps. Notice high relative power of all wavelengths. SPD diagrams can also be very useful in understanding how various lamps differ in the color composition of their light output. All incandescent light is produced by heating a tungsten filament until it radiates light. In a sense, this is the way light is produced by the sun. It follows, therefore, that incandescent lamps exhibit smooth SPD curves, like sunlight. Such continuous spectra typically produce less significant changes in object colors than narrow lines spectral lines. Compare the daylight spectral power distribution or incandescent lamp (narrow band sources) with that for a fluorescent or mercury lamp (narrow band). The most obvious difference is the generally lower level of power compared to daylight, and the discontinuous spectrum. All wavelengths are again present but only certain wavelengths (the spikes) are strongly present. These spikes suggest which parts of the color spectrum will be emphasized in the rendering of color for objects illuminated by the light source. For example, the reduced amount of red energy is fairly obvious, when we look at the SPDs for narrow band sources, especially the mercury vapor lamp. In practical terms, we can imagine that a red object, such as a ripe apple, would look very appealing under the incandescent bulb and very dull under the mercury lamp.

2.5. SPECTRAL REFLECTANCE OF AN OBJECT

The color of an object is produced by the interaction of that object with the energy from a light source. The object will selectively absorb or reflect the



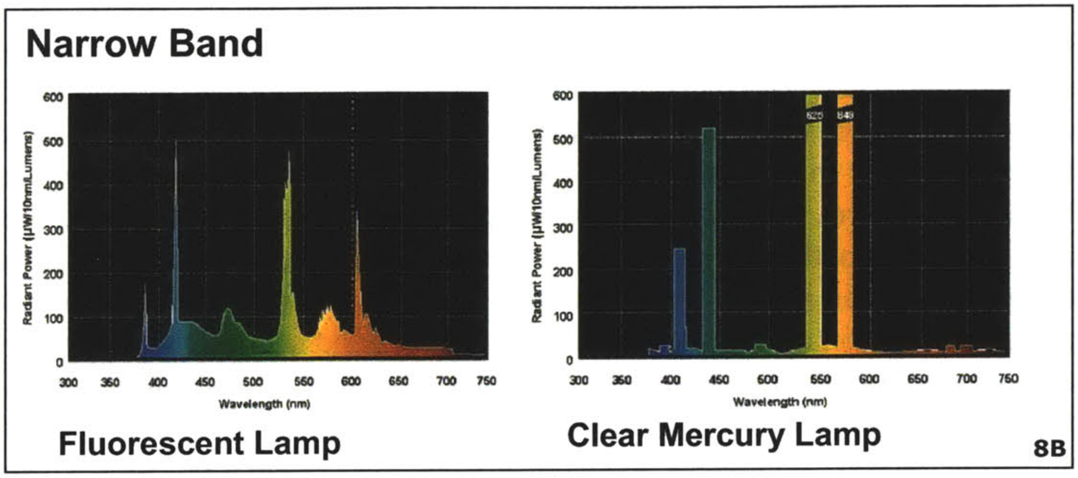


Figure 8A & 8B – Spectral power distributions (SPDs) for broad band and narrow band light sources. Pictures from http://www.gelighting.com/na/.

energy from the light source that strikes it. When all the wavelengths are reflected equally, our eye sees white or gray, absorption of all energy yields black, while selective absorption of specific wavelengths results in color. The object selectively absorbs or reflects light, and the observer sees (senses) the color. Each of these plays a critical role in the observation of color and each must be numerically characterized in order to be able to describe color precisely.

Blue ink (or blue pigments) reflects blue light in the region of 450 nm and absorbs light in the other portions of the spectrum. In other words, the ink reflects more blue light back to the observer while attenuating the remaining wavelengths of the visible spectrum. Red objects reflect red light in the region of 600 - 700 nm while absorbing the remainder of the visible light. Yellow objects reflect light at wavelengths above roughly 540 nm while absorbing light at shorter wavelengths. When a spectrophotometer measures a colored surface, it determines the amount of light reflected from a sample in small increments throughout the visible spectrum. This provides a unique spectral reflectance curve for each color (Williamson & Cummins, 1983). From this spectral reflectance curve, color numbers such as color difference, strength, and even color formulation can be derived (Figure 9).

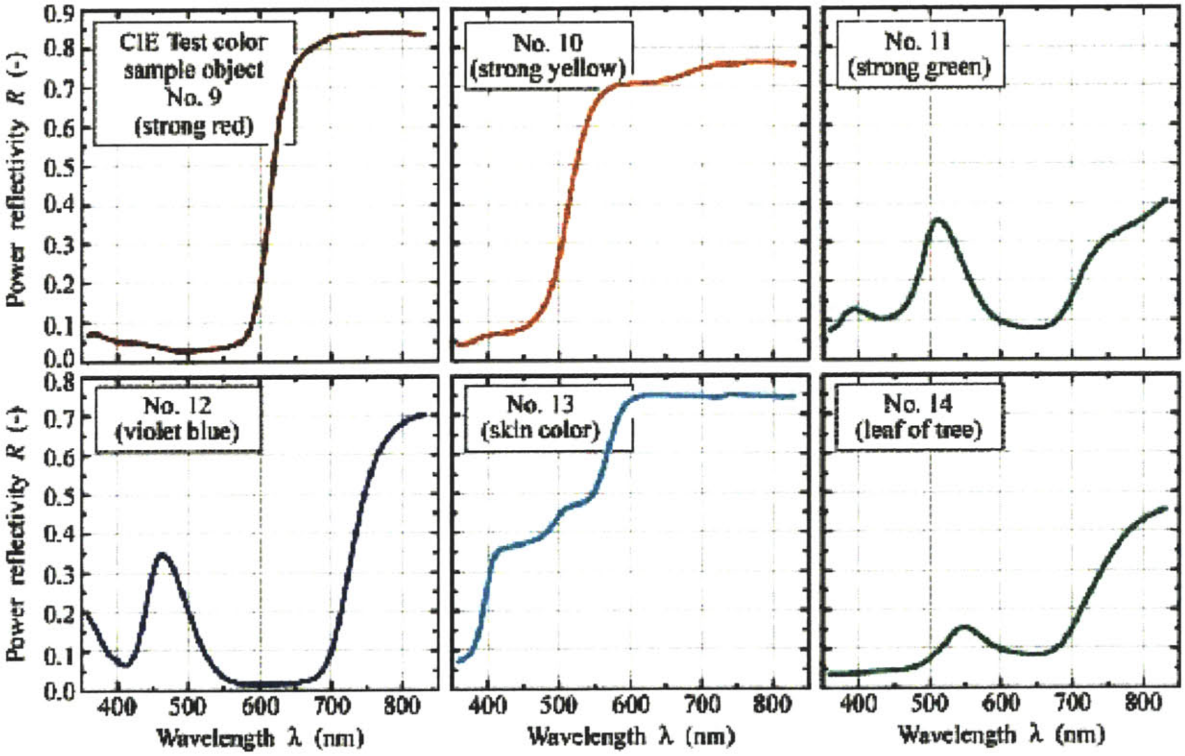


Figure 9 - Spectral power reflectivities of the CIE test color samples used to calculate the special color rendering indices. Data after CIE, 1995. Picture fromwww.lightemittingdiodes.org.

2.6. CHROMATICITY COORDINATE AND CIE CHROMATICITY DIAGRAM

The spectral power distribution (SPD) of a light source carries a complete description of the color properties of the light source. However, it is not straightforward to interpret a SPD curve. Simpler and more convenient measures are necessary for everyday applications. One of them is the practice of locating a color as a point (x, y coordinate) in a diagram called a "color space" (IESNA, 2000).

As it was mentioned previously on the "Color Vision" section, the CIE data for the color sensitivity of an individual eye is expressed in terms of the three spectral sensitivity functions (or color matching functions) x, y, and z (figure 5). To obtain the chromaticity coordinate of a particular white light, its spectrum should be weighted by the xyz color matching functions(CIE/ISO 10527, 1991), and from the resultant three weighted integral values (tristimulus values X, Y, Z), the chromaticity coordinate x,y is calculated by the formulas:

$x = X/\ (X+Y+Z)$

$y = Y\ /\ (X+Y+Z).$

A specific method for associating three numbers (or tristimulus values) with each color is called a color space. In the study of the perception of color, one of the first mathematically defined color spaces was the CIE 1931 color space, created by CIE in 1931, as a results from a series of experiments done in the late 1920s (Boynton, 1979; Fairman & Hemmendinger, 1998). In this CIE color space, the tristimulus values are called X, Y, and Z, which are also red, green and blue imaginary primaries. The chromaticity of a color is specified by the two derived parameters x and y which, as shown in the formulas above, are the fractions of X & Y respectively. This way the color of a surface or light can be expressed by a point or the chromaticity coordinate x, y on the CIE 1931 chromaticity diagram, as shown in figure 10. The boundary of this diagram is the plot of monochromatic lights, called the spectrum locus, with wavelengths shown in nanometers. Plotted near the center of the diagram is the line called the Planckian locus, which is the location of all chromaticity coordinates of a blackbody at temperatures from 1000 K to 20000+ K. The region around the Planckian locus above about 2500 K can be regarded as

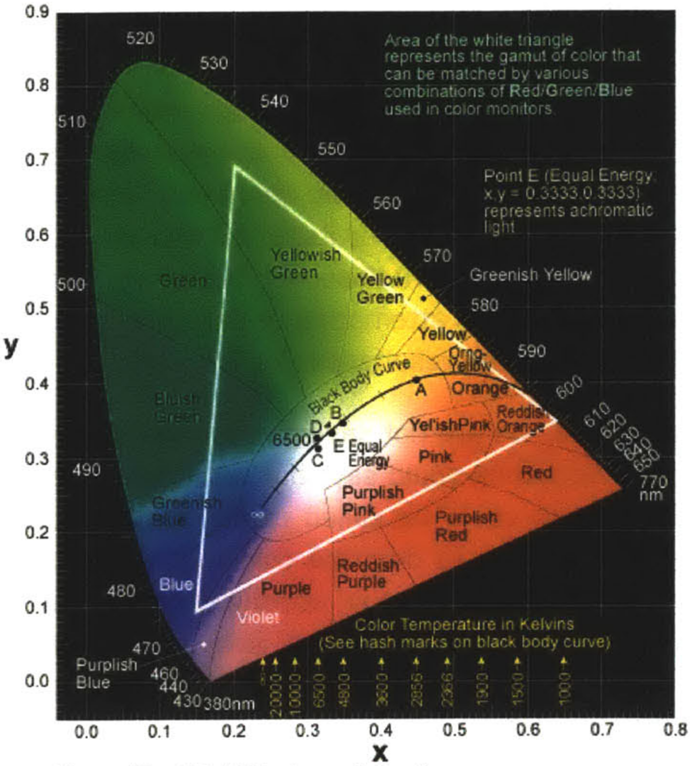


Figure 10 – CIE 1931 chromaticity diagram.

white, 2500 K being "reddish white" and 20000 K being "bluish white". The colors of most traditional lamps for general lighting fall in the region between about 2700 K and 6500 K.

Chromaticity coordinates have many uses. One is to suggest the relative appearance of two or more colors. A color space can be extremely helpful but still it may not be found straightforward to mentally interpret the appearance of light using chromaticity coordinates. A scientific community made of color, vision, and lighting specialist have developed methods that allow approximation of the human's main color perceptions. There are metrics used to describe the appearance of light emitted from a light source (color temperature); and there are methods which are focused on explaining the color appearance of objects when illuminated by a light source (color rendering); these metrics involve also the relationship with the luminous efficacy (lumens per watt). These metric are presented as follows, but, as it will be clear as this document unfolds, due to the complexity of the visual system, these measures are only approximations, and their usefulness is limited for lighting practice

2.7. THE CIE LAB COLOR SPACE

As mentioned previously, the process of sensing color requires the combination of three separate components: a light source, an object, and an observer. We have just examined how each of these components can be quantified: a light source by a spectral power distribution SPD, an object by its reflectance curve, and an observer by either the CIE 2° or 10° standard observer. Therefore, it is necessary to include all three components when attempting to describe color. If one of these three components is varied, the resultant color will vary.

When we describe an apple as being red, we are not saying much about the color even though we said its name. Someone could say: but what red? The apple could have different shades of red, could be called candy apple red, blood red, catsup red, rose red, etc. In order to describe colors accurately, they need to be characterized three different perceptual attributes of human color vision: *hue*, that is, the red, orange, yellow, etc. aspect; *saturation*, that is, how much color of any hue is present; and by lightness, that is, the degree of *lightness* or darkness of a particular color.

By using an illuminant's spectral power distribution, SPD, and a standard observer, the light reflected from any one object can be converted into the *hue*, *saturation*, and *lightness* descriptions for any color. Additionally, a sample can be compared to any standard with these same three attributes. In 1976 the CIE adopted a color space for identifying color attributes, known as 1976 CIE L*a*b* (or CIE Lab) Color Space (Fairchild, 1998). It uses the designation of Dh to signify a hue difference between a sample and a standard, the designation of DC* to signify a difference in saturation (or chroma) between a sample and a standard, and the designation of DL* to signify a difference in lightness between a sample and a standard. Thus, by using these three terms, hue, lightness, and saturation, we can describe the attributes of any color, or the difference between a sample and a standard. There are two other terms that are occasionally used to describe color: a *red/green* color difference and a *yellow/blue* color difference. CIE Lab Color Space assigns the designation Da* for a difference in red/green value and the designation Db* for a difference in yellow/blue value.

Early in the 1900's, Albert Munsell, a professor at an art school in Boston developed a color order system, named the Munsell system (Munsell Color

Services, 2004), which offered a means to name colors. With a published system, people could be specific about which red they were referring. Many other color systems exist today and are used for research and common practice. Munsell's system can be compared to the Pantone color system, TRUEMATCH, CIE systems and others.

2.8. COLOR TEMPERATURE

A common single number description for the color of light from a whitish light source is known as *color temperature*. It indicates the color appearance of the light source when it is viewed directly (figure 1). Color temperature may appear to be a somewhat surprising quantity, as color and temperature would not seem to have a direct relationship with each other. However, the relationship is derived from the temperature of a blackbody radiator that has the same chromaticity as the white light source; at increasing temperatures it glows in the red, orange, yellowish white, white, and ultimately bluish white (Wyszecki & Stiles, 1982). The color of its radiated light depends only on a single number, its temperature. The temperature is given in units of the kelvin where the Kelvin temperature is the Celsius temperature plus 273. Color temperature comprises the set of chromaticity coordinates that fall along the *blackbody locus*, the curved line in the central region of the chromaticity diagram, where of all blackbody temperatures (whitish light sources) can be plotted (figure 10).

A somewhat more general metric to define color temperature called the *Correlated Color Temperature* (CCT). This refers to the blackbody temperature at this closest possible visual match when an exact chromaticity match cannot be made. Very few artificial light sources (except for some incandescent lamps) have chromaticities exactly on the blackbody locus, and therefore most lamps are actually described in terms of CCT rather than color temperature. Lines of constant CCT have been drawn across the blackbody locus on the chromaticity diagram so that one can still simply plot the chromaticity of a light source to find its CCT. If two lamps have the same CCT, it does not mean that they will have exactly the same color appearance because their chromaticities can be at different points along a line of constant CCT (IESNA, 2000).

Light of lower color temperatures is interpreted as having a warmer appearance or ambience while light of higher color temperatures is interpreted as having a cooler appearance. For example, an incandescent lamp at about 2800 K normally is judged warm while light from the blue sky, possibly about 12,000 K, would be judged cool. This warm-cool dimension have nothing to do with the temperature of the blackbody radiator (the thermal temperature of the actual light source is not the temperature indicated by the value of its color temperature although they may be similar for some light sources) but refer to the way color groups are perceived—the perceptual impact of lighting. To a great extent, white depends on the color adaptation of the eye and the various sources of light in the space. As an example, light from either a 3000 K or a 4100 K fluorescent lamp generally is accepted as white light when it is the principal light source in a space. However, if the two lamps are seen next to each other, the 3000 K appears warm (yellowish) while the 4100 K appears cool (bluish); white is judged somewhere between. Now if the 4100 K lamp is seen next to a 5500 K florescent lamp, the 4100 K lamp will appear warm (table 3).

2.9. BRIGHTNESS

As mentioned before, brightness can be defined as how the human visual system responds to light; or how bright the average human eye judges a light to be and it varies, depending on the color of the light (Lotto & Purves, 1999). B*rightness* (subjective perception) and *luminance* (physical) may be quite different depending on the hue and saturation differences between the color fields compared. In fact, one of the largest discrepancies between the human perception and the system of colorimetry and photometry is generally known as the Helmholtz-Kohlrausch effect (Yaguchi & Ikeda, 1980). There are many examples of this effect, but essentially it involves the situation where colored lights of equal luminance may not appear to be equally bright. This is because the brightness of light reflected from a surface is not a linear function of the actual reflected light. Under special circumstances two lights of equal brightness (but unequal luminance) can appear *less* bright when they are combined than when either is seen alone, a rather disturbing result for those who have a superficial understanding of photometry and colorimetry.

2.10. COLOR RENDERING

While color temperature is an indicator of the appearance of light, it cannot describe the mix of wavelengths present in the light. How we see object's colors depends on the wavelengths emitted by the light source, the wavelengths reflected by the object, the surroundings in which we see the object, and the color-vision characteristics of the visual system (figure 11). Our conception of the color of an object is a constantly changing, highly dynamic process. It is important however to visualize the color effect in space, and then be able to specify the light sources to make it happen. A property called Color Rendering (CR) can be thought as the ability of a white light source to render the colors of an object. It is a very common misconception that the color of an object depends only on the properties of the object itself. However, as George Palmer first found in 1777, the perceived color of an object equally strongly depends on the illumination source (MacAdam, 1993). Illuminating colored test samples with different light sources, he found that 'red appears orange' and that 'blue appears green'. This is because objects have reflectance properties whereby each wavelength in the spectrum of incident light is absorbed or reflected to a varying extent. Thus, the 'true color' of an object requires that we have a particular reference illuminant in mind. Typically, light sources that are considered to provide good color rendering are those which render colors similar to what they would look under daylight, or under another full-spectrum source, such as an incandescent lamp.

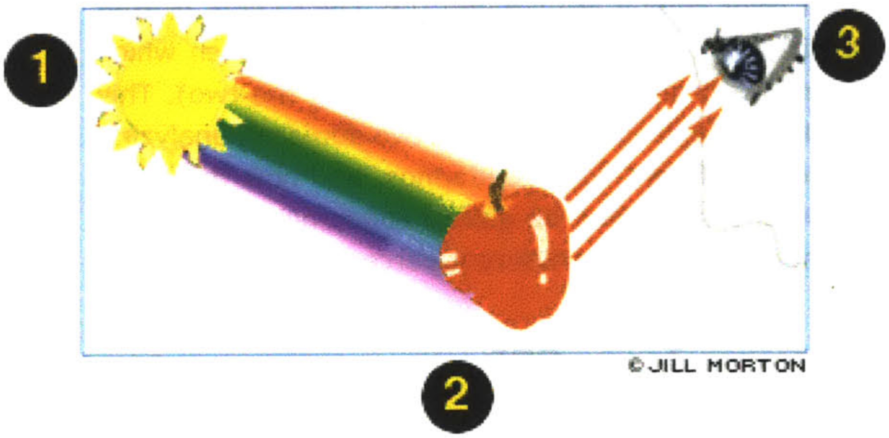


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Figure 11 - How we see object's colors depends on the wavelengths emitted by the light source, the wavelengths reflected by the object, and the color-vision characteristics of the visual system.

The study of color rendering is concerned primarily with the color shifts that occur when one illuminant is exchanged for another (Thornton, 1971; Worthey, 2003). For certain exchanges of illuminants of different chromaticities, object colors change, but the visual system is able to discount the illuminant, and perceived object colors change little (and unnoticeably). This phenomenon called color constancy. In other cases, the change in illuminant can generate object's color differences that are visible (figure 12), even if the illuminants have the same chromaticity (look alike). Imagine a room with a number of light bulbs visible. If those lamps are not closely matched in color temperature (i.e. same chromaticity), it is likely that people will notice. On the other hand, imagine another similar room with bulbs that all have the same color temperature. These lights are a pleasing white color when viewed directly (or reflected off of a neutral white surface), but when these lights illuminate colored objects in the room, red and green colors may show up as black or brown. A visitor who steps into the room will experience the problem, but he will have trouble trying to explain what is happening. He may say for instance that the room is "dark" (which we will see in further sections is true in a sense), even if not true to an illuminance meter. These lights create an even worse problem than do the lights different in chromaticity, but the user is less able to describe where the issue is. This is a color rendering problem. This problem is not vague or mysterious; it is physical and measurable; it is just hard to verbalize.

Color rendering can be analyzed from a physicist approach, focused on the physical process by which color stimuli are created (i.e. color shifts plotted in the CIE chromaticity diagram); or by a color perception approach which is how color stimuli is perceived; or both (i.e. by comparing the two). This thesis research work is going to be dealing with these two domains, analyzing both the physical measure of different color renderings, and how these are perceived by the human eye. Insights will be gained concerning basic color mixing, color-difference metrics, and color different perception.

2.11. COLOR RENDERING INDEX, CRI

When incandescent lamps started to be replaced by fluorescent lamps as the common indoor light source, a large variety of SPDs were added to the previously ubiquitous incandescent SPD and a simple metric was required for applied lighting considerations. Although there were earlier alternative proposals, the Color Rendering Index (CRI) was the first metric that appeared to have practical value and gained wide acceptance (CIE, 1995). CRI is a unit of measure that defines how well colors are rendered by different illumination conditions in comparison to a standard illuminant (i.e. daylight) of equal color temperature.

When CRI is calculated, it can be rated on a numeric scale with a maximum of 100. On this scale, a CRI value of 100 represents that all color samples illuminated by the test source appear to have the same colors as those same samples illuminated by the reference source. That is 100 represents no perceived difference in color appearance, and therefore, in theory, a high CRI value indicates that a light source will render the colors of an object similar to the colors when illuminated by a continuous spectrum of similar color appearance (table 3). The reference source is always chosen to have the same CCT as the test source. It is also from a series of relatively smooth spectra such as incandescent lamps. In practice, however, the CRI value can be misleading in indicating the rendering capability of narrow band light sources. Such a light source may obtain a high CRI value and still render certain colors poorly, or vice-versa; or even two lamps with same CRI may render colors completely differently. This occurs because of the nature of the CRI concepts.

The CRI value results from an algorithm such that the magnitude of visually judged color differences can be reasonably well predicted (when the SPD is known). During the procedure, the magnitude of difference for 14 color samples under test and reference sources is perceptually judged. These samples were selected from the Munsell color system, and the calculations are based on their spectral reflectances. The color difference for each color sample is calculated (quantitatively in terms of color coordinates, no longer just qualitatively). This value, weighted by a pre-factor, is then subtracted from 100. This results in the CRI value. The set of 14 color samples was selected for reasonably well predict colors observed in real life scenes; The average CRI calculated from the eight samples (samples 1 through 8 which are not highly saturated) is called the General Color Rendering Index, or Ra. Samples 9 through 12 are saturated red, yellow, green, and blue respectively; sample 13, or R13 , represents caucasian flesh tones, and sample 14 or R14 represents green foliage. CRI values evolving from these six samples results in what is called Special CRI, designated as Rn (n = sample calculated).

The lighting industry uses the CRI of lamps as a descriptive color metric and it is almost exclusively the averaged value, Ra. The United States Energy Policy Act, (U.S. Public Law 486, 1992) specifies the minimum color rendering indices as well as the minimum efficacy of common lamps (Table 3). But the CRI value, as a single number, cannot convey much information. What CRI can do best is to inform how close or how far we are from a reference source. A common impression of CRI is: the higher, the better, which is implicit in much of the lighting literature. However CRI has nothing to do with correctness, desirability, or preference. For example, the special CRI R9 is principally a measure of the spectral power above about 630 nm (i.e. color sample used for R9 is a highly saturated red). R9 can be included along with Ra as part of lamp descriptions, indicating how well the light source will render saturated reds. However, we should note that even most of the common high color quality (CRI of 85 or above) fluorescent lamps will have relatively low R9 values; that is saturated reds may look dull under such light sources (Worthey 1982, 2003). It is easy to show that preferred light source colors often are below a CRI of 100. If the CRI is low, it is important to look carefully at the source to see if it is acceptable for a specific purpose. If the CRI is high, it is unlikely that the source will promote serious distortions of object "true" colors.

Figure 12 - Demonstration of visual effect of different color rendering on fruits.

LIGHT SOURCE	COLOR TEMPERATURE	COLOR RENDERING
Natural Sunlight	5000-6000k	100 CRI
Candle	1700k	100 CRI
Incandescent	2700k	100 CRI
Tungsten Halogen	3200k	95 CRI
Fluorescent (Cool White)	4200k	62 CRI
Fluorescent (Daylight)	6400k	80 CRI

Table 3 - Color Temperature (CCT) and Color rendering (CRI) values for several light sources.

2.12. COLOR RENDERING AND ENERGY EFFICIENCY

Energy efficiency of light sources involves (1) efficiency of conversion from electrical power (W) to optical power (radiant flux) (W), (measured in percentage with no unit); and (2) conversion from radiant flux (W) to luminous flux (lumen = lm), which is a value determined by the spectral power distribution, SPD, and is called luminous efficacy of radiation, LER, (unit in lm/W). In general, the lighting community uses the term luminous efficacy, as a measure of how efficiently the light source converts input power (Watts) to light (Lumens). It is practical to separately consider luminous efficacy in terms of monochromatic radiation (i.e. colored light, or stimulus per wavelength), and in terms of white radiation (i.e. white light, or a mixture of colored radiations).

Because our eyes do not respond to all wavelengths the same way, we perceive some colors to look brighter than others. Luminous efficacy is therefore driven by the human eye spectral sensitivity demonstrated by the $V(\lambda)$ function. The luminous efficacy of colored light is straightforwardly shown by the $V(\lambda)$ curve which describes efficacy per wavelength. For example, colored light at 450 nm has luminous efficacy of only 26 lm/W whilst the peak of the curve occurs at 555 nm with an efficacy of 683 lm/W (theoretical limit). That means, if placed beside all other colored lights of same power, a yellow-green light (single wavelength at 555 nm), would appear the brightest to the human eye, its luminous efficacy being 683 lm/W (Boynton, 1979; Le Grand, 1968). The same considerations apply for white radiation or white light, but then the spectral power distribution, SPD, of a mixture of colors and not simply a single wavelength is considered. The SPD, of the white mixture must be weighted with the eye's response, and again the efficacy of such light will be driven by the eye sensitivity function. In this case, a high luminous efficacy can be attainable if the spectral components of the white light favor those wavelengths to which the eye is most sensitive. A white light containing strong radiation on the 555 nm region will be more efficient that another light that is richest in wavelength in the 450 nm region. The maximum efficacy for white light (color temperature of 3000 K) has been calculated to be approximately 500 lm/W[1] and is a mixture of only two wavelengths, 450 nm and 580 nm.

By selecting the wavelengths and adjusting their luminous intensities individually, the spectral power distribution of a white LED can be strategically designed to have high luminous efficacy. It has been shown however that when mixing narrowly peaked wavelengths, the luminous efficacy and color properties are interrelated, as that there is a fundamental trade-off between color rendering and luminous efficacy (Thornton, 1971). One of the two quantities can be maximized only at the expense of the other. For example, dichromatic LED lamps (i.e. white light from mixing blue and yellow radiations) can offer very high luminous efficacies (> 400 lm/W) but result in extremely poor color rendering that is not appropriate for architectural lighting. On the other hand, tri-chromatic and quadric-chromatic lamps (mixings with RGB, or RGB + Yellow radiations) can offer high color rendering (CRI in excess of 80 points) but will result in reduced luminous efficacies. The exercise of color mixing re-working the spectrum of white light according to this fundamental trade-off constitutes the basis of this thesis research.

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[1] The luminous efficacy of radiation is a theoretical maximum that a light source with a given spectral power distribution can achieve with a 100% radiant efficiency (efficiency of conversion from electrical power in W to optical power, or radiant flux, also in W). It has been shown that it is theoretically possible for a RGB white LED to have a maximum about 500 lm/W, which means that source efficacy of 200 lm/W should be possible. Such high efficacy ratios would be for an "ideal" source, i.e., without any loss. The actual efficacy of a real source would be lower because no source operates at 100% efficiency. This is the rationale for the US Department of Energy's solid-state lighting goal of 200 lm/W (Navigant Consulting, Inc., 2006).

CHAPTER 3. RELATED WORK: LIGHTING

3.1. THE RELATIONSHIP BETWEEN LAMP SPECTRUM AND VISUAL PERCEPTION.

The desire for a numerical description of the colorimetric performance of artificial illumination is at least as old as the introduction of discharge lamps[1] in early 1930s. When fluorescent lamps were introduced, in early 1940s, this interest further expanded due to the fact that fluorescent technology enabled the manipulation of white light's spectral components. Then, researchers became more interested not only in such a *numerical description*, that would result in the metrics and standards based upon spectral properties; but also in a *qualitative description*, that could help develop models to predict visual response to lighting, and hence the "appropriate spectral qualities" for each environment. The creation of the fluorescent tubes generated a "boom" in the lighting research community at the time. Many attempts were made to relate numerical values to the perception phenomena; as well as efforts to create

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[1] Unlike incandescent lamps, gas discharge lamps have no filament and do not produce light as a result of something solid getting hot. Rather, the atoms or molecules of the gas inside a glass, quartz, are ionized by an electric current through the gas in proximity to the tube. This results in the generation of light usually either visible or ultraviolet (UV). The color of the light depends on both the mixture of gasses or other materials inside the tube as well as the pressure and type and amount of the electric current. Fluorescent lamps are a special class of gas discharge lamps where the electric current produces mostly invisible UV light which is turned into visible light by a special phosphor coating on the interior of the tube (Coaton & Marsden, 1997).

a colorimetric framework for numerical evaluation of color rendering, color preference, visual performance and visual comfort. A very similar scientific enthusiasm is taking place today with LEDs as the novel light source. As mentioned before, LEDs, like fluorescents, are narrow band sources which allow full control of their spectral composition. Like in the past, researchers are faced today with the need for a numerical description as well as a qualitative description of the colorimetric performance of this new revolutionary light source.

Early experiments using fluorescent lamps have shown, for example, that certain lamps provided greater visual quality than others, indicating that subjective reports may indeed correspond to a measurable dimension of experience (Bellchambers et al, 1969, 1972; Thornton & Chen, 1978). There has been extensive research investigating the influence of the spectral composition of white light sources on visual perception to assist the general lighting industry. Prior to the introduction of LED technology, this type of research was mainly characterized by qualitative assessments of appearance involving psychophysical methods of visual comparison between two light sources of different colour properties: a narrow-band test source (i.e. fluorescents), and a full-spectrum reference source. These experimental works were conducted at photopic levels typical of interior lighting and used three main techniques listed which use *apparent brightness* as an example of criterion:

- Side-by-side visual matching: subjects are exposed to adjacent identical interiors and asked to adjust the illuminance of one interior until the two interiors are equally bright. It yields numerical data in the form of illuminance levels at equal brightness.

- Brightness ranking: sequentially presents two sources of fixed illuminance, from which the observer identifies which is the brighter;

- Subjective rating (semantic scales): the observer is required to rate the brightness (or pleasantness, colorfulness, etc) of an interior on a seven-point scale from *dim* to *bright*.

An effect normally referred to as Visual Clarity was vastly studied, and was believed to be a combination of several individual factors such as perceived brightness, color rendering, color discrimination, color preference, and border sharpness. Most experiments investigating visual clarity have been performed under fluorescent light.

When fluorescent lamps were first introduced, the only guiding principle was that lamps for general lighting should give an impression of "whiteness", and closer study revealed that white is far from a well defined color. The question arose as to what color of white would be desirable. The fact that it was possible to vary the SPD of a fluorescent lamp, led to investigations regarding first the most desirable color for that light; than discrepancies in color rendering; and later the relationships between these properties.

3.1. Early Experiments in Color Temperature

In 1941, a Dutch researcher, A.A. Kruithof (1941) published a graph showing that color temperature preference changed based on the intensity of the light within a space. According to the Kruithof's curve, an observer prefers lower color temperature lighting when the light level is lower, and prefers a higher color temperature when the light level is higher. In essence, he suggested that at low intensities there was a narrow range of pleasing color temperatures (i.e. 2200–2500 K at 50 lux); as intensity was increased, the color temperature range broadened and shifted towards higher values (i.e. 2700–3600K at 200 lux).

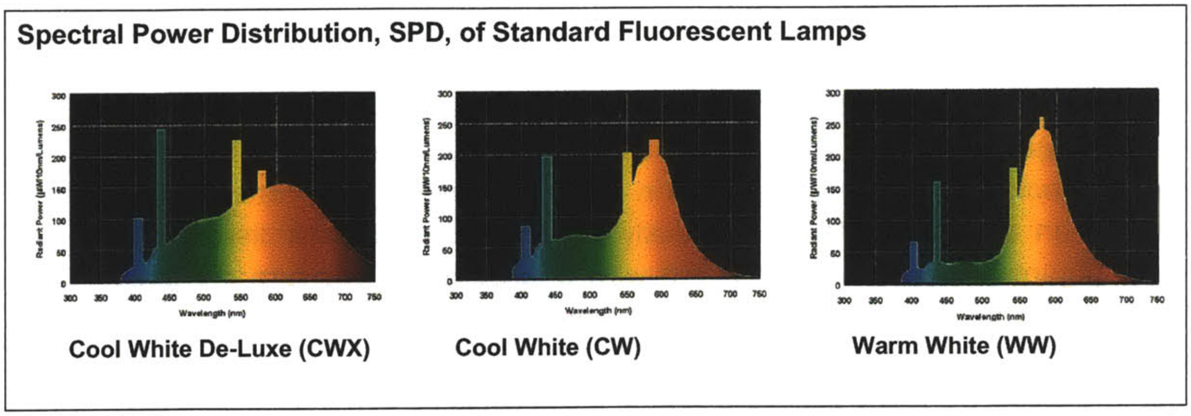
Harrington (1954) found that as the color temperature increased, the illuminance needed for equal brightness perception decreased. He used brightness matching to compare two projection screens viewed side by side illuminated by incandescent lamps with different color temperatures (5380K, 5620K and 6260K) and matched in brightness. The results suggested that stimulus of higher CCT were perceived as significantly brighter, as the majority of observers found that less light of the higher color temperature was needed to produce the same brightness. Harrington concluded that the average gain in apparent brightness was 1 percent per 100'K color temperature difference in the range 5400-6300K. If the observer had time to color adapt, as in continuous side by side screen viewing, an increase in the apparent brightness of the higher color temperature screen resulted.

3.2. EARLY EXPERIMENTS IN COLOR RENDERING

The following research projects represent rigorous experimental work specifically dedicated to Color Rendering, which took place on late 1950s, early 1960s. They were selected not only for they strong contribution to the community at the time, but also to illustrate how strikingly similar the challenges of the early days of fluorescent technology were to our challenges today with LED systems.

In 1957 Kruithof wrote a comprehensive description of practical experimental work on color rendering whereby he explained that choosing phosphors with a great diversity of spectral distributions as the component for the mixture, could have two main goals: (1) Give the lamps the highest attainable luminous efficiency; (2) Make the color rendering of the lamps as good as possible. He provided a detailed description of how mixtures of various phosphors in a tubular fluorescent lamp could result in different color points, how the first standard fluorescent lamps were generated, and further evolved from the optimum luminous efficiency version, with low color rendering (i.e. cool daylight, warm white-WW, color white-CW), to versions with lower luminous efficiency but better color rendering (called "de Luxe" lamps, i.e., CWX); which further evolved into lamps with still superior color rendering and lower efficiency (called "Tri-phosphor" lamps) (figure 13). He explained that the color rendering of these lamps was improved by adding red to the spectrum and attenuating the blue-violet radiation. The general calculation for the mixing and optimum degrees of absorption was outlined, and new mixtures of phosphors suggested.

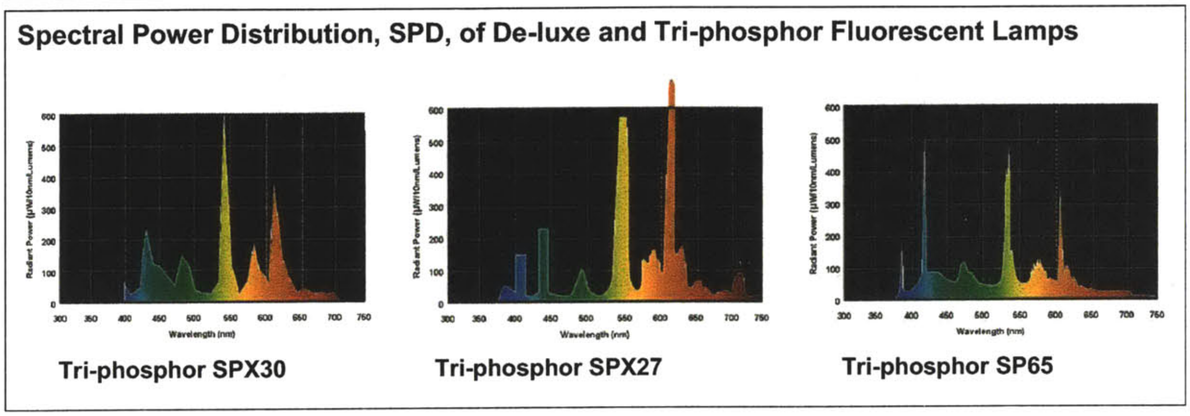
The growing awareness of the importance of color rendering, made it important to measure it. In the search for a color rendering metric, it was agreed that daylight was the reference for 'ideal' color rendering, and the critical question was: "how much and in what ways can an illuminant differ from what it imitates and still remain an acceptable imitation? That is, within what tolerances must the illuminant lie?" Early psychophysical experimental work using the criterion of accurate color rendering was carried out by Crawford (1955, 1959, 1960,1961). His work resulted in the 'spectral band' method, a pioneer method of determining the color rendering properties of illuminants by direct psychophysical measurement. It was based on determining the



Cool White De-Luxe (CWX)

Cool White (CW)

Warm White (WW)



Tri-phosphor SPX30

Tri-phosphor SPX27

Tri-phosphor SP65

Figure 13 – Typical spectral power distribution, SPD, of standard types, de-Luxe and of tri-phosphor (prime-color) fluorescent lamps. Picture from Pictures from http://www.gelighting.com/na/.

degree of variation from an ideal color rendering (i.e. daylight) which could be tolerated. The determination of spectral band tolerances was carried out for certain applications and these tolerances were incorporated into a system of assessment and specification of color rendering. Another method, the 'color shift' method, was found to be more reliable and resulted in the first official CR metric, the Color Rendering Index, CRI. But the investigations on the band method provided valuable results to the understanding of the nature and importance of color rendering, and of particular interest to this work.

The essence of the spectral band method was to divide the spectrum into a number of bands, or regions. The criterion used was a *just noticeable difference* from the standard when judged by memory only. In the typical experiment the spectral composition of the light by which a test object was seen was altered gradually and continuously until the observer judged the object not to look as it did to begin with (1955, 1959). By making the rate of change sufficiently slow the observer's state of adaptation followed the change closely enough and he would be completely unaware of the changing conditions, until, of course, he noticed that the appearance of the test object had changed. A rate of change was determined such that the experiment section took from 3 to 6 minutes. In order to produce the variable light source, an apparatus with continuously variable spectral transmission was used (figure 14). This was a system with a large prism aperture designed to disperse the light from a tungsten filament lamp into a spectrum, then recombined it and project it onto the test object. When the light was spread out into a spectrum any desired shape of mask could be inserted to stop part of the light and so alter the spectral composition of the test light. The visible spectrum was divided into six bands (i.e. 400, 450, 510, 540, 600, 630, 760 nm or violet, blue, green, yellow, orange, red). A shutter was provided for each band, and the fraction of each which could be removed before it was noticed was determined. Such fractions were the actual tolerances to be measured. Results were expressed in terms of 'band general tolerance' (for practical conditions, where a scenery picture was used as test object) and 'band special tolerance' (where test objects such as foodstuffs and human complexion were used). As a result, a color rendering diagram was made that rated lamps according to tolerances. A few examples of fluorescent lamps

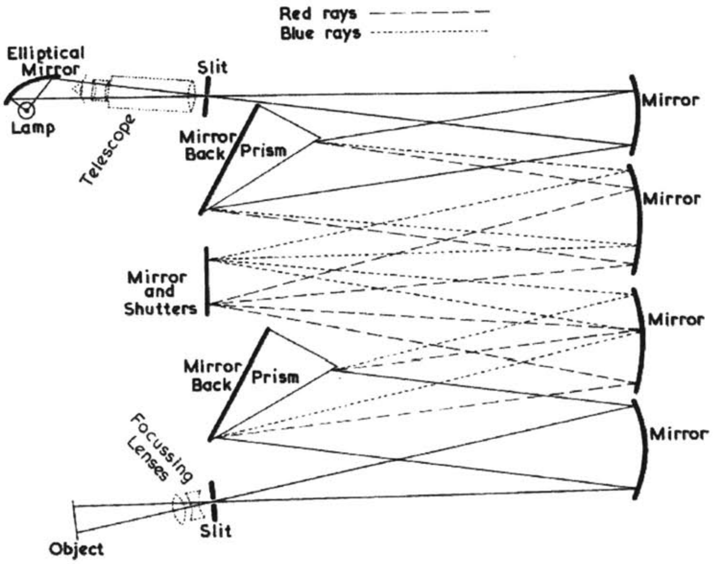


Figure 14 – Apparatus used by Crawford for determination of color rendering tolerances; general plan of optical arrangements. The lightly dotted telescope and focusing lenses show a modification whereby the observer could look at the test object through the apparatus; this gave a larger field of view and increased level of illumination, but only monocular viewing. Picture from Crawford (1963).

were classified by this type of assessment.

The next step in Crawford's investigations (1960, 1961) was to bring the tests from the laboratory work to a practical scale. Test objects were a wide selection of pictures and museum pieces, and the tests took place at art museums in London. These experiments were carried out in the following way: a light source was made up of such type of 'daylight' fluorescent, of obvious color rendering deficiencies, supplemented by other lamps which made up for the deficiencies of the fluorescent lamps (figure 15). The latter lamps were continuously dimmed (i.e. dimming a proportion of the lamps, some red and some blue-green) so that the color rendering of the composite light source was at first perfect, then could be gradually transformed to the imperfect fluorescent lamps (figure 16). The gradual change from 'ideal' to 'distorted' was then initiated, and proceeded in a steady rate, the total change taking about three minutes. Each observer then recorded the moment at which he noticed a change (figure 17). This moment could also be predicted, on the basis of the previous laboratory work. Agreement between predicted and actual values went a 10% way towards confirming the validity of the laboratory measurements. On the basis of this study it was then possible to assess the suitability of a light source for a particular purpose with a fair

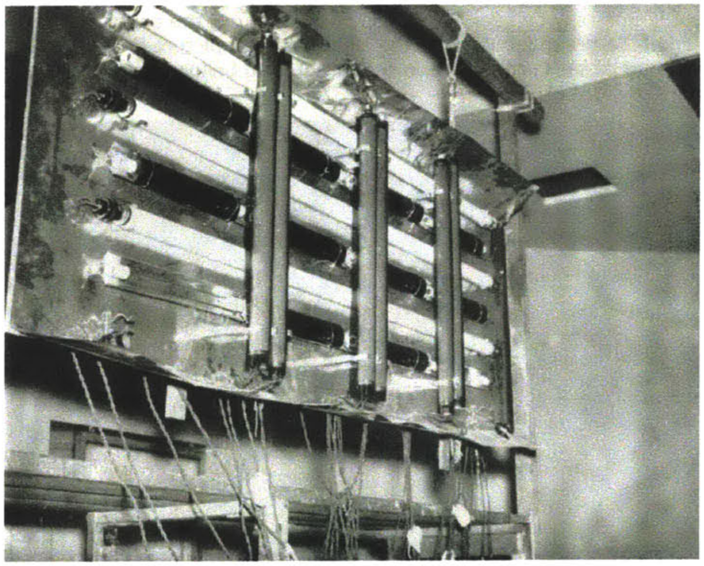


Figure 15 – The lighting unit used in Crawford's full scale experiment in London Museums. Light from fluorescent lamps was supplemented by blue-green light (short vertical fluorescent lamps with filters) and red light (horizontal tungsten strip light with filters) so that the whole array closely approximated black body radiation at 4200 K. By dimming a proportion of the red and green lamps it was possible to transform the quality of light from fluorescent lamps from "ideal" to "highly distorted". Picture from Crawford (1961).

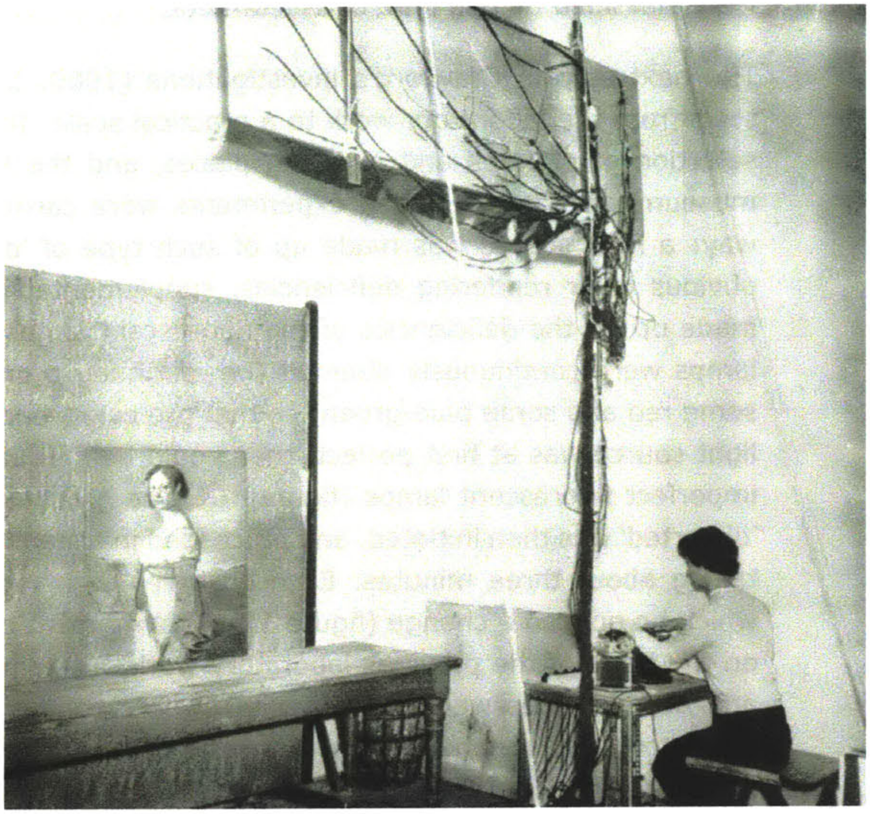


Figure 16 – The general layout apparatus used for the Museum experiments. The array of fluorescent lamps may be seen at the top of the picture, the controller for dimming the red and blue-green lamps is on the right, the test picture is on the left and the observers stood or sat in the space in the foreground bellow the array of lamps. Picture from Crawford (1961).

Figure 17 – A general view of the scene at a section of the color-rendering assessment at the Victoria and Albert Museum in London. The test objects are on the left. Picture from Crawford (1961).

amount of certainty. Spectral band analysis could also assist in the design of a light source.

The work of Hennicke (1959) is also of particular interest, as she also carried out experimental work in which the criterion of a *just perceptible change* was used. She worked with a number of fluorescent lamps of six types, widely differing from each other in spectral power distribution, but all close in color temperature to an incandescent lamp (2856K), used as the reference source. The six types of fluorescent were compared with it one at a time. The apparatus was arranged so that an observer looked at color samples on a grey background, illuminated *alternately* by the reference standard and by the test lamp. The arrangement of apparatus is shown in figure 18-a. For each test

No color difference	**0**
Hardly noticeable color difference	**1**
Definite color difference	**2**
Large color difference	**3**
Very large color difference	**4**

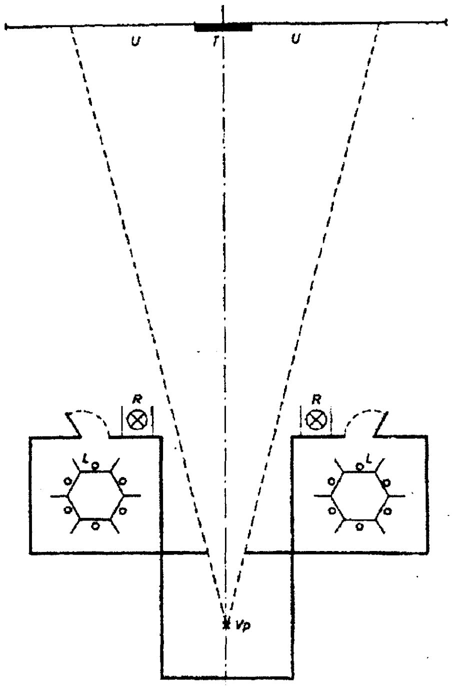


Figure 18 - (a) plan of apparatus used by Hennicke for color rendering experiments. Vp, observer; L, L, fluorescent test sources; R, R, tungsten reference sources; U, U, grey background; T, test color sample. (b) Semantic scale used for color difference assessment.

illuminant, the observer was asked to assess the change in appearance of the colored test patch according to the scale (figure 18-b):

3.3. EARLY EXPERIMENTS RELATED TO VISUAL CLARITY

The balance between illuminance and lamp color properties for equal satisfaction using the term visual clarity was first reported by Bellchambers and his colleagues (1969, 1972). Three standard fluorescent lamps were compared to a special fluorescent lamp using prime-color technology and of higher color rendering called Kolor-rite. The spectral power distribution of the Kolor-rite lamp had an increased blue and green component, with defined peaks in red, green, and blue wavelengths. Two separate visual clarity experiments were undertaken, one using a color box and another using a full-size room. Two identical scenes were placed side-by-side for comparison, and were illuminated with identical luminaries, each having mechanically-controlled light output designed to maintain, at all illuminances, the same intensity distribution. Subjects were asked to adjust the sources to the illuminance required for equal clarity. In both experiments, the authors concluded that Kolor-rite lamps provided higher color rendering and greater visual clarity than the other lamps; and that measured that it required significantly less illumination (approximately 25% less illuminance) than the other sources to provide an equal clarity effect. An approximate 10% saving in power per unit area was possible by using prime-color (deluxe) lamps (Lemaigre-Voreaux, 1970).

Boyce (1977) identified problems in the validity of Bellchambers' results and also wanted to check the extent to which the results were associated with the high saturation colors used. He carefully examined the trade-off between illuminance and color rendering properties, and measured visual clarity as the reduction of illuminance for equal satisfaction, and the gamut areas of the two lamps were compared. Boyce set up an experiment with a scaled model of an office whose colors were more typical on an interior environment (figure 19). Again, two identical chambers were placed side-by-side for comparison, and clarity was measured by adjusting the illuminances between two standard fluorescent and Kolor-rite lamps. Bellchambers' results were all validated. Using the same set-up Boyce developed a further study of preference between the tested lamps using semantic scales for ratings of pleasantness, colorfulness, satisfaction and visual distinctness. Scenes lit by Kolor-rite rated higher in most cases and required approximately 25% lower illuminance than regular fluorescent lamps for equal satisfaction. The relationship implied that the larger the gamut area of a lamp, the greater the reduction in illuminance for equal satisfaction, and that gamut area relationship to brightness perception would most likely hold true. Boyce also confirmed that Bellchambers' results applied to a wide range of interior colorfulness, affirming that the level of colorfulness of the illuminated scene did not have a significant effect on illuminance differences for equal satisfaction. Examining Boyce's complete set of results, we can also see that CRI and Gamut Area

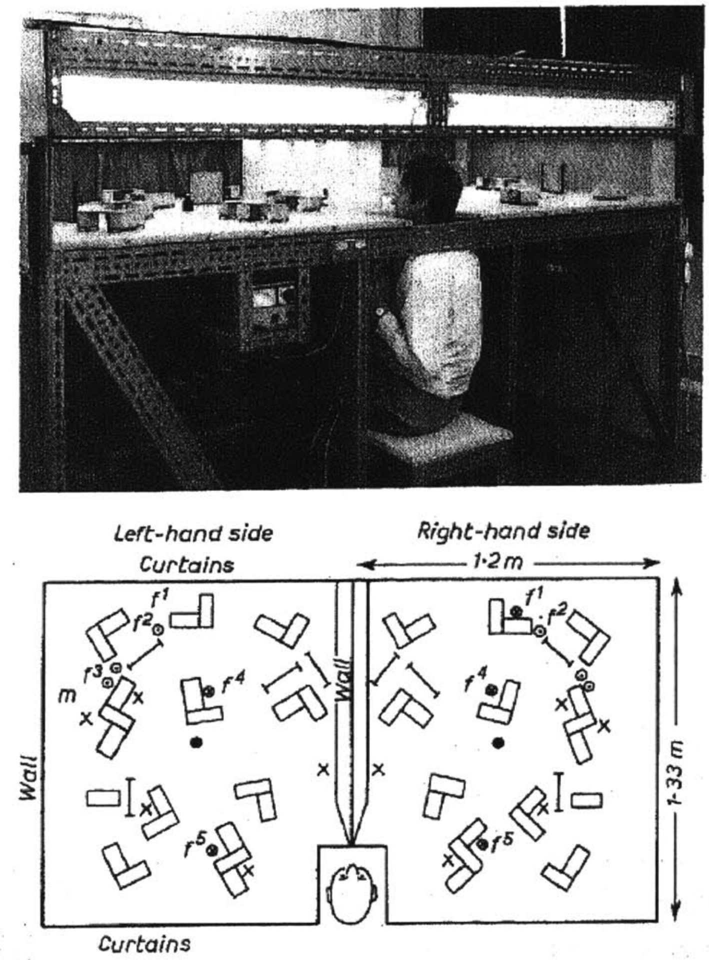


Figure 19 - Photograph and plan of Boyce's (1977) apparatus.

give a better prediction of the results than does color temperature, as color temperature did not seem to cause any perceptual difference or cause any source to rate higher in Boyce's experiments.

Thornton and Chen (1978) promoted the fact that artificial sources can have their spectral composition tuned in accordance with the three peak response from human vision for maximum *visual clarity*. Fluorescents based on three peak response principle were called prime-color or tri-phosphor lamps, and have a different spectral power distribution compared to standard fluorescent lamps (figure 13). There are three defined peaks in such lamp's spectral power distribution at approximately 435 (Red), 540 (Green), and 610 nm (Blue), which correspond well with human vision estimated spectral peaks at 450, 540, and 610 nm. His results confirmed that a tri-phosphor fluorescent lamp offered greater visual clarity than the standard white fluorescent lamp, using a set-up with simultaneously illuminated adjacent large enclosures, furnished with colorful objects. Observers were asked for equal overall clarity, measured as a function of illuminance as in Bellchambers' experiments. He measured a 40% lower illuminance from the tri-phosphor lamp to give equal clarity (later re-calculated to 20%). Subjects were also asked to chose their preferred between two scenes of equal brightness. The author attributed superior tri-phosphor performance to the three spectral peaks RGB related to human vision spectral sensitivity, suggesting that peaks at these regions provide the best color perception with minimal power input.

Worthey (1982) suggested that an opponent-colors model provides a convenient basis for computing certain color-rendering properties of an illuminant. The opponent color theory (Boynton, 1979; Le Grand, 1968) says that the three types of cones (Red, Green and Blue) feed into chromatic neural channels (Red-Green R-G; Blue-Yellow B-Y); and also feed into a luminance channel. Red-Green contrasts have been known to enhance the sharpness of borders and feed the luminance channel, while Blue-Yellow contrasts add to the luminance channel but do not increase border sharpness. The tri-phosphor peaks provide spectrum needed to produce R-G and B-Y contrasts. The color rendering properties would be related to the possibility of a light of systematically minimized or exaggerated color contrasts in the red-versus-green and blue-versus-yellow dimensions. He also suggested that the opponent-colors formulation provided a basis of understanding the relationship between color rendering and visual clarity.

Worthey developed two parameters to rate lamps in terms of Color Rendering: 't' and 'd'. A larger value of 't' meant the red and green colored surfaces would be enhanced; likewise a larger 'd' meant blues and yellows would appear more saturated. He measured a number of different lamps and found, for instance, that a 4100K tri-phosphor fluorescent lamp had a significantly higher value of 't' than a standard cool white lamp of comparable CCT. The tri-phosphor lamp also had a greater value of 'd'. It was clarified that the quantities of 't' and 'd' described systematic gains or losses of saturation that could be expected in the average case. In an empirical way, then, Worthey showed that color rendering, and in particular the parameter 't', could be the important independent variable for the puzzling data regarding visual clarity. He suggested that the performance of a light as an illuminant could be specified by a set of five numbers: *{A, t, d, i, 2}*. The first three numbers corresponded to the usual intensity and chromaticity, enough to describe the light when directly viewed. The last two describe the appearance of objects illuminated by the light. Noting that 't' and 'd' controlled contrasts at borders it was shown that in a realistic illumination situation, the visual system tends to ignore A, t, and *d;* 't' and 'd' however, described the features of the illuminant that it could not ignore. He expressed examples such as that of the standard Cool White fluorescent lamp which reduced red-green contrasts by about 21% and exaggerates blue-yellow contrasts by about 4%.

In a further experimental work, Worthey (1985) reported that increased red-green contrasts (especially tri-phosphor lamps) increased border distinctness, and hence visual clarity, in comparison with a standard fluorescent. In this study, he used two side-by-side booths with identical set of colored papers (i.e. Red-Green & Blue/Yellow paper test pairs). Subjects were asked to dim the lights in one booth until borders on each booth appeared equally distinct, and to adjust the illuminance for equal brightness. An increased clarity effect was attributed to the tri-phosphor lamps, as they required less illuminance for equal border distinctness of red/green pairs. No difference was recorded between lamps for brightness.

DeLaney and team (1978) questioned the results of experiments with simultaneous exposure of two different sources. On their tests, each eye was stimulated simultaneously with 2sec. occlusion of eyes between scenes.

Seven different fluorescent lamp types were judged. Two identical pictures of colorful cave scene presented in side-by-side rooms. Both a test for color discrimination; and semantic rating scales for subjects' appraisal were used. Delaney's work conflicted Thornton's results as his comparison between the prime-color and the deluxe lamp resulted in overall insignificance of the preferences between lamp types on the semantic scale. In fact, color discrimination was adversely affected under the prime color lamps. His overall conclusion was that it was hard to choose a specific lamp on the basis of color; and suggested a possible disassociation between the concepts of clarity and satisfaction. Delaney's claim was that our visual system is not composed of three narrow color receptor systems, but it is composes of three, rather broad overlapping color receptor system plus one very broad achromatic system; and the narrower the three peaks the greater the color distortions. He cited some reliable research findings which had shown the three peak illuminants resulting in color mismatches and poor color discrimination.

Boyce and Cuttle (1990) used rating scales to investigate the subjective impression of an interior illuminated by fluorescent lamps of different CCT and at different illuminance levels. They compared four fluorescent lamps of CCT 2700, 3500, 4200 and 6300K, each of CRI in the range 82–85, using a 5-point rating scale applied to lighting in a room. Observers rated visual sensations such as *bright* and *dim* on a scale from 'very much so' to 'not at all so'. The authors concluded that color temperature in the range 2700 K–6300 K had *little* effect on observers' impressions of the lighting. In the colored rooms the 6300 K source was rated as less bright than the 2700 K and 3500 K lamps. This disagrees with Harrington's results (1954) showing stimuli of higher CCT to appear brighter. Interestingly, in an achromatic room ratings of '*dim*' were significantly affected by CCT, the lamps being ranked 2700 K, 6300 K, 3500 K, 4200 K in order of dimmest to brightest. These results suggest that in side-by-side assessments CCT differences cause a difference in perceived brightness that is not apparent when observers are adapted to a single stimulus.

Twenty years after the work above had been published Vrabel (1998) and Fotios (2001) re-visited the visual clarity issue, and wanted to check some of the conflicting information resulted from investigations on the tri-phosphor fluorescent lamps. They presented their own results together with a detailed survey on the past work.

Vrabel and his colleagues (1998) showed that it was found on previous experiments (Harington, 1954; Aston & H E Bellchambers, 1969; Boyce, 1977; Thornton & E Chen, 1978) that lighting systems of high CR lamps (specifically prime-color) needed lower illuminance than systems with standard fluorescent lamps for equal perceived brightness of a colorful scene. They ran experiments to further investigate visual clarity in view of conflicting information from other results on deluxe and prime-color lamps. They compared five lamps *in sequence* in a full-scale test room by 29 observers. Two main techniques were used: (1st) Seven point semantic differential scaling for warm/cool, edge sharp/dull, bright/dim, colorful/less, clear/hazy, un/natural, des/like, un/pleasant; and (2nd) brightness rating (paired brightness perception). In Vraibel's study the positive visual clarity ratings of tri-phosphor lamp verified most of the previous clarity work in terms of increased color, brightness and clearness. They showed that the higher color rendering lamps, including a tri-phosphor, produced greater sensation of visual clarity, compared to the others with respect to colorfulness, clearness, and brightness. Significant correlation was found between ratings of colorfulness and brightness, suggesting that higher brightness is predicted by higher values of both CRI *and* CCT, but on their own these descriptors can fail in such a prediction. Vrabel also noted that higher CR lamps provided a greater brightness perception. Moreover, Vraibel's results were particularly supportive of Thornton's work (1978) from the colorfulness scale, and of Worthey's results (1985, 1982) from the positive ratings for tri-phosphor lamps on the clear/hazy scale. Worthey's measure of 't' and 'd' would further explain the positive ratings for the tri-phosphor lamp. However, it is very important to note that in Vrabel's experiments the high grade halophosphor lamp, rated equal to the tri-phosphor on the clear/hazy scale, but did not have the same spectral peaks.

Results from Fotios (1997) showed that it was possible to reduce the lighting power per unit area by using lamps which yield maximum visual clarity and brightness: Sodium HID required 100% more illuminance than warm white fluorescent. For same perceived brightness; Full-spectrum fluorescent Required 20% less illuminance than standard fluorescent; Tungsten filament with blue filter required 25% less illuminance than regular bulb. He used side-by-side matching technique with simultaneously illuminated both, and concluded that lamps of higher CRI and CCT were set to lower illuminance at same apparent brightness and again were most preferred. Fotios later published an extensive research review (2001) that reports on most studies on visual clarity, specifically interested in the relationship between SPD and apparent brightness. Experiments were seeking reliable evidence to show whether lamp color properties did significantly affect the perceived brightness, hence to establish the magnitude of the effect. Only eight among the 21 studies were considered valid and reliable, as he also reports on studies that must be discounted due to the presence of experimental bias or experimental errors.

Fotios' reported that most results showed a significant difference between illuminance and apparent brightness when comparing lamps of different spectrum. The main conclusion from Fotios' survey indicates that: (1) Sources with higher CCT and higher CRI require lower illuminance for equal perceived brightness; (2) Color rendering exhibit better correlation with illuminance ratio at equal brightness than those relating to color appearance; (3) Neither CCT, CRI or Gamut Area alone make good predictions of the brightness response, and combining attributes of CCT and CRI will provide a more reliable prediction. He also provided the following analysis: considering two scenes, the scene under illuminant with higher CCT and CRI will appear brighter. If the lamps have similar CCT, the illuminant with higher CRI will appear brighter. Likewise, if the illuminants have similar CRI the one with higher CCT will appear brighter. An illuminant with higher CCT but lower CRI, will appear less bright than another illuminant having the higher CRI but lower CCT.

The visual clarity concept, after 30 years history; was still poorly understood. Thornton claimed that, although visual clarity was never defined semantically, it could be undoubtedly defined visually by the observers. It seemed to be identified unmistakably under prime color lamps, when compared to conventional fluorescent illumination, especially in large, real-life installations. It was not clear whether a visual clarity component existed, or if the concept was multidimensional. There existed a consensus among most experts, from Bellchambers to the CIE Color committee, that visual clarity was both real and important, but what it was and how it was produced or measured remains a mystery.

3.4. CONCLUSION

Looking at the work of these scientists we conclude that the evaluation of the chromatic aspects of light sources is a rather complex phenomenon, ranging from color rendering through preferred rendering, and color discrimination to visual comfort. Those conclusions can be listed as follows:

- It was found that lighting systems of high CR lamps needed lower illuminance than low CR systems for equal perceived brightness of a colorful scene (Harington, 1954; Aston & Bellchambers, 1969; Boyce, 1977; Thornton & Chen, 1978; Vrabel et al, 1998). In fact, lamps with higher values of both CRI *and* CCT were found to be perceived brighter and were most preferred.

- Color rendering exhibited better correlation with illuminance ratio at equal brightness than those relating to color appearance (Boyce, 1977; Vrabel et al, 1998). According to Fotios (2001), when two scenes are under illuminants of similar CCT, the illuminant with higher CRI will appear brighter. Likewise, an illuminant with higher CCT but lower CRI, will appear less bright than another illuminant having the higher CRI but lower CCT.

- High color rendering lamps may require less illumination, because they provided a greater brightness perception. Consequently, it may be possible to reduce the lighting power per unit area by using lamps with high CR which yield maximum perceived brightness. For example, an approximate 10% saving in power per unit area was possible by using prime-color lamps as for same perceived brightness (Lemaigre-Voreaux, 1970) as 25% less illuminance was measured from high CR lamps to give equal apparent brightness (Harington, 1954; Aston & Bellchambers, 1969; Boyce, 1977).

- It became clear that the spectral quality of the lamp depended on the choice of phosphors composing the fluorescent mixture. The question was then: what wavelengths should be used for best CR, maximum apparent brightness, and border sharpness? Thornton (1978) showed that artificial sources could have their spectral composition tuned in accordance with the three peak response from human vision for maximum *visual clarity*. Therefore, according to his findings, lamps that have their peaks at these regions (i.e. the prime-color lamps Kolor-rite and tri-phosphor) could provide best color perception with minimal power input. Likewise, Worthey (1982, 1985) found that the tri-phosphor peaks provided spectrum needed to produce R-G and B-Y contrasts, which supports Thornton's claims.

- A general conclusion driven from most authors' results that at that time, choosing phosphors as components for the fluorescent mixture could have two main goals: (1) Give the fluorescent lamps the highest attainable luminous efficiency; (2) Make the color rendering of these lamps as good as possible. This happens to be the exact same challenge that the lighting community is facing today using color mixing strategies for multi-chip LED systems.

The results from the above research review showed that the most appropriate criteria for judging the performance of a light source had yet to be found. The relationship between lamp spectral composition and apparent brightness was still not fully understood after a long history of investigation. This could be thought of as an even more complicated issue, if we consider that, in real life architectural spaces, colors stand in a complex relation to one to another, the relation being of great psychological import, yet outside the scope of colorimetric specification.

CHAPTER 4. LEDS & COLOR

4.1. LEDs & WHITE LIGHT

A light-emitting diode or LED consists of a chip of semi-conducting material (a semiconductor diode) that converts electrical energy to light, solely by the movement of electrons in the semiconductor material (Zukauskas, Shur & Gaska, 2002). The basic structure of a light emitting diode consists of a chip of the semiconductor material (commonly referred to as a die); a lead frame on which the die is placed and bonded to the anode and cathode terminals of the frame through miniature bonding wires (figure 20). The entire assembly is encased in the appropriate housing, containing the optical and thermal management devices appropriate for the desired application. LED arrays or clusters can be built using several methods, and each method depends on the manner in which the chips themselves are packaged by the LED semiconductor manufacturer. Examples of packaged LEDs are shown in figure 21.

The mechanism of light generation in LEDs is called electroluminescence. More precisely, injection electroluminescence, which inherently, in semiconductors results in light emission within narrow spectral bands. Therefore a LED is considered a narrow band source. In LEDs the wavelength of these bands, and therefore the color of the light generated, depends on the semi-conducting

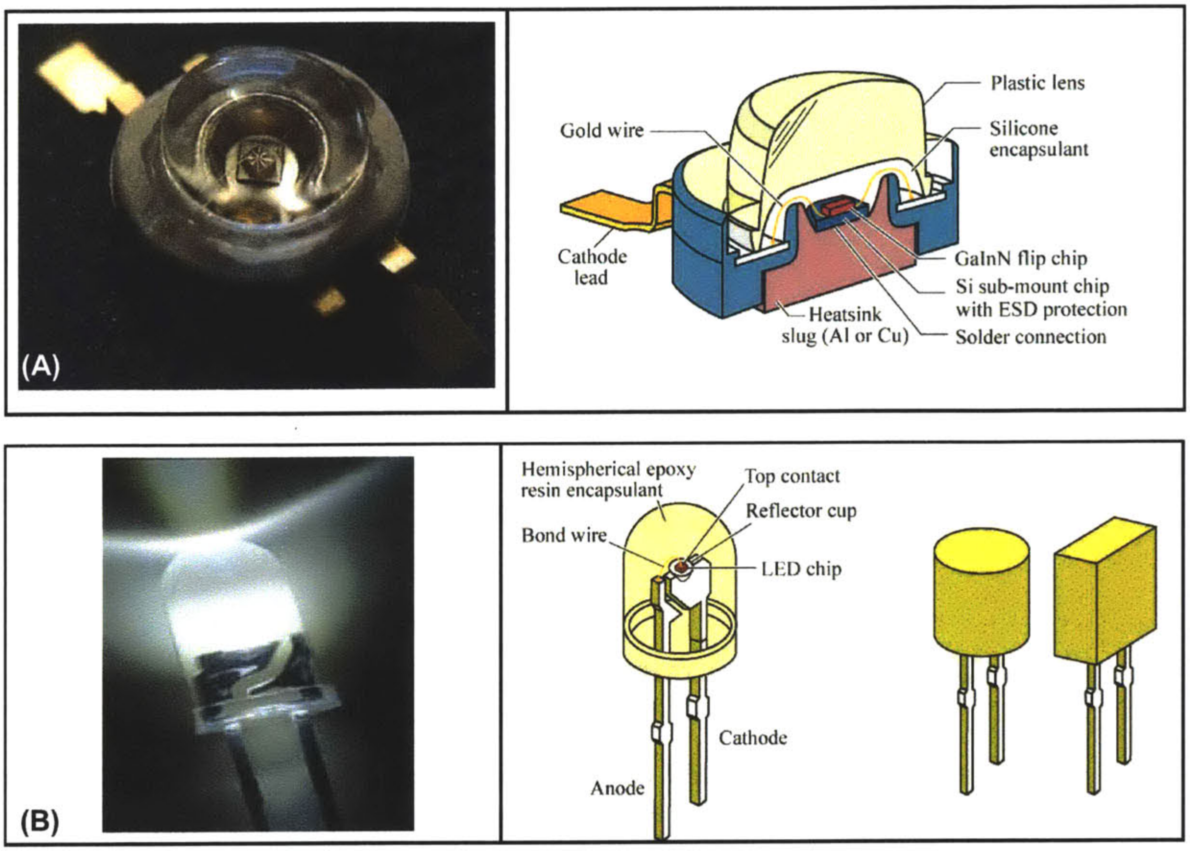


Figure 20 - LED Packaging: (A) Cross section through high power (>1 Watt input) LEDs package. It can be soldered to a printed circuit board. This package in particular is called "Barracuda" from Lumileds Corp. (B) Typical standard LED packages: spherical, cylindrical and rectangular encapsulant. Data and picture from www.lightemitting.diodes.org.

material[1] used (figure 22). But architectural illumination requires light that is perceived as white. Alone, LED chips are not well suited for general illumination applications as they do not produce the white light required in these applications. White light LED systems are typically based on one of two common approaches: (1) Phosphor-conversion LEDs (Nakamura & Fasol, 1997; Mueller-Mach & Mueller, 2000). That is, combining a blue LED with a conversion

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[1] Typically, commercial high-flux LEDs suitable for general lighting are based on aluminum-indium-gallium nitride (AlInGaN) alloys for blue and green emissions (roughly 440 to 550 nm), and aluminum-indium-gallium phosphide (AlInGaP) alloys for amber (585 to 595 nm) and red (615 to 645 nm) emissions.

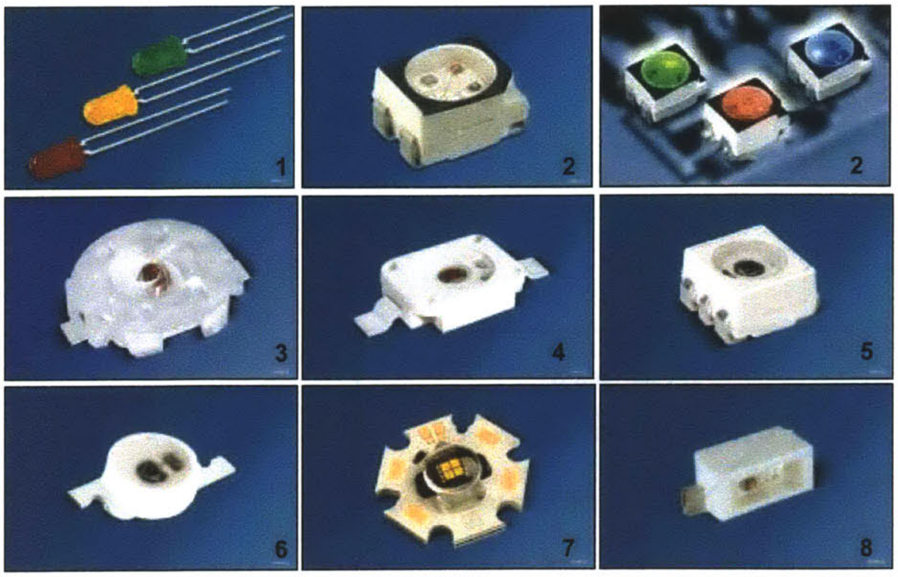

Figure 21A – Examples of packaged LEDs. From Osram Opto Semiconductors: (1) 3 mm (T1) Standard LED; (2) Multi Color Top Emitting LED; (3) Golden DRAGON® ARGUS®, with Lens; (4)Golden DRAGON®,1.4 Watt LED; (5)TOPLED®; (6) PointLED® Round package, high assembly flexibility, symmetric radiation pattern; (7) OSTAR-Lighting: High brightness LED in multi-chip on board technology, hexagonal shape; (8) Micro SIDELED® Low height side emitting light source. Pictures from: (http://www.osram-os.com/).

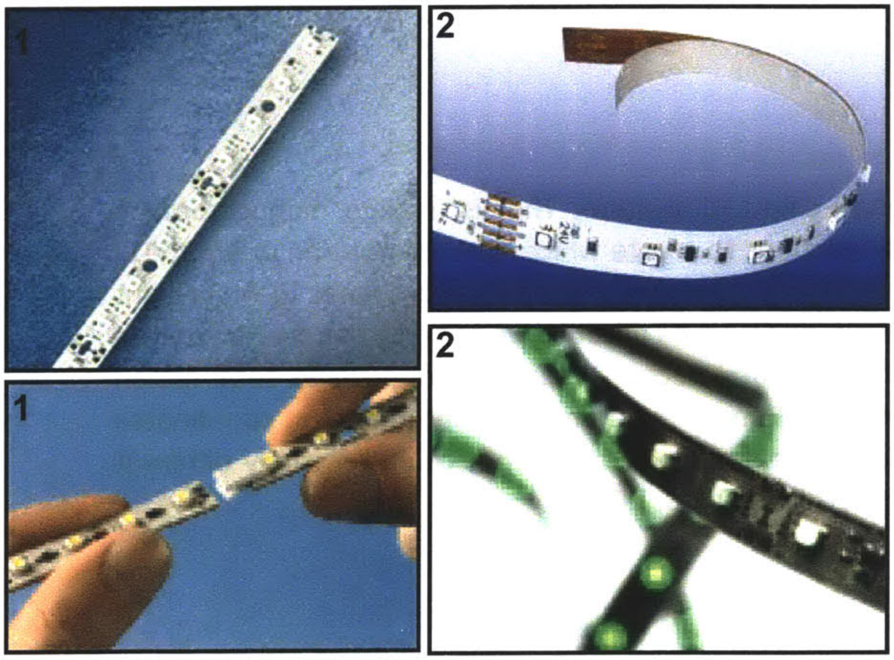

Figure 21B – (1) LED Module: LINEAR Light; (2) LED Module: LINEAR Light Flex. Pictures from: (http://www.osram-os.com/).

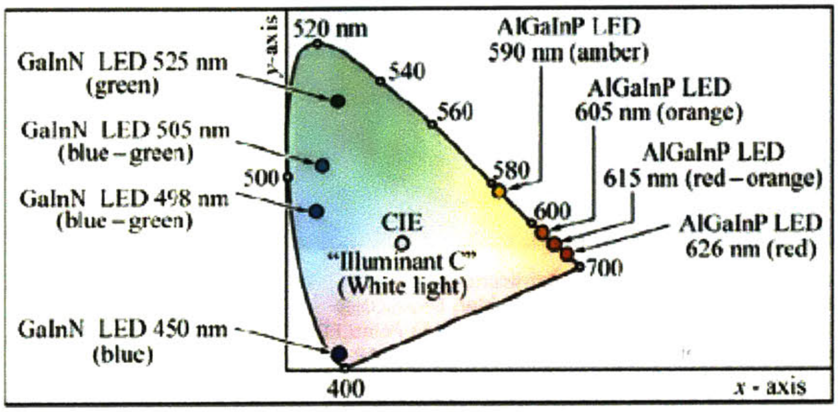

Figure 22 – Location of LED light emission on the CIE Chromaticity Diagram. Data and picture from www.lightemittingdiodes.org.

phosphor[2], and (2) Multi-chip LED system. That is, mixing monochromatic LEDs in appropriate proportions to create white light (Narendran et al, 2001; Zukauskas et al, 2001). Figure 23 shows these two approaches to white-light production. Although both approaches produce white light, the characteristics that are relevant for general architectural illumination, such as total lumen output, luminous efficacy, lumen maintenance, chromaticity coordinates (CIE x, y), color temperature, and color rendering, could be vastly different (Mueller-Mach & Mueller, 2000; Ohno, 2005).

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[2] The combination of yellow and blue light appears as "cool" white light to the human eye, with color temperatures ranging from roughly 5000 to 8000 K. Proprietary red-emitting phosphors may be added to produce "warm" white LEDs with color temperatures in the range of 2800 to 3500 K.

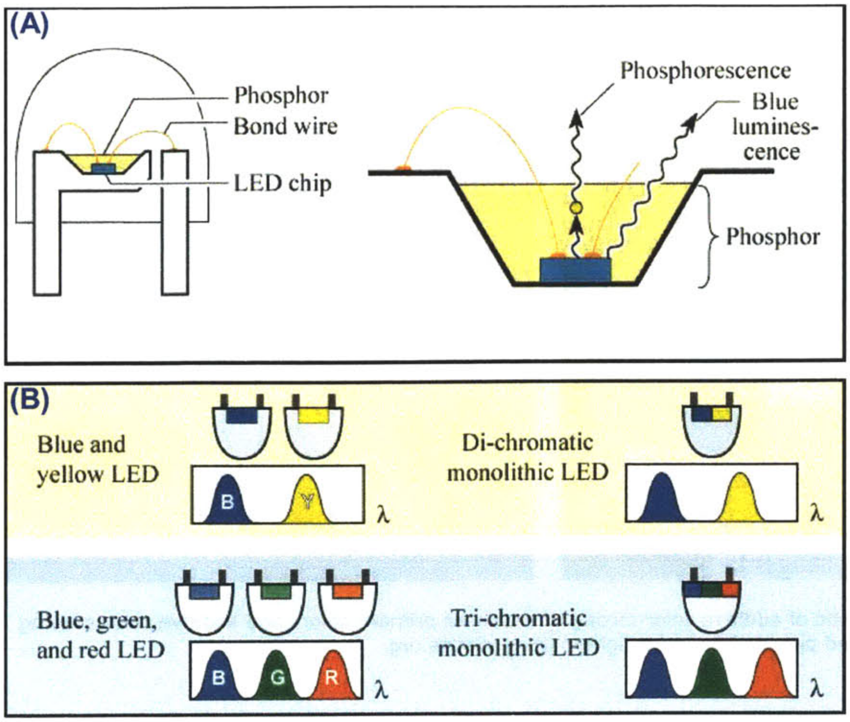


Figure 23 – Examples of two different approaches for LED white light production: (A) conversion phosphor, which uses a blue LED and yellow phosphors to create white light; and (B) Color-Mixing LED approach, which mixes the light from individual monochromatic LEDs to create white light. Picture shows a single chip approach and multi-chip, dichromatic and tri-chromatic LED clusters.

4.2. LEDs & Color-Mixing

This thesis research work is focused on the multi-chip color-mixing approach, which starts with colored LEDs and uses color mixing optics to blend together the light output from the individual sources. In order to understand white lighting from multi-chip LEDs it is important to understand the basic principles of color mixing. Although the complete spectrum of light shows that white light contains a continuous range of many wavelengths (colors), the colors from just two or more areas of the spectrum could be mixed to form white light. For example, like shown in figure 23, LEDs of peak wavelengths on two (yellow and blue) or three (red, green, and blue) regions of the spectrum can be mixed to create white light (Zukauskas et al, 2001). When two, three or more colors of colored light are mixed, the intensities of each individual light are being added, and this type of mixing is called additive color mixing (Judd & Wyszecki, 1975). Figure 24 shows a schematic additive color mixing of

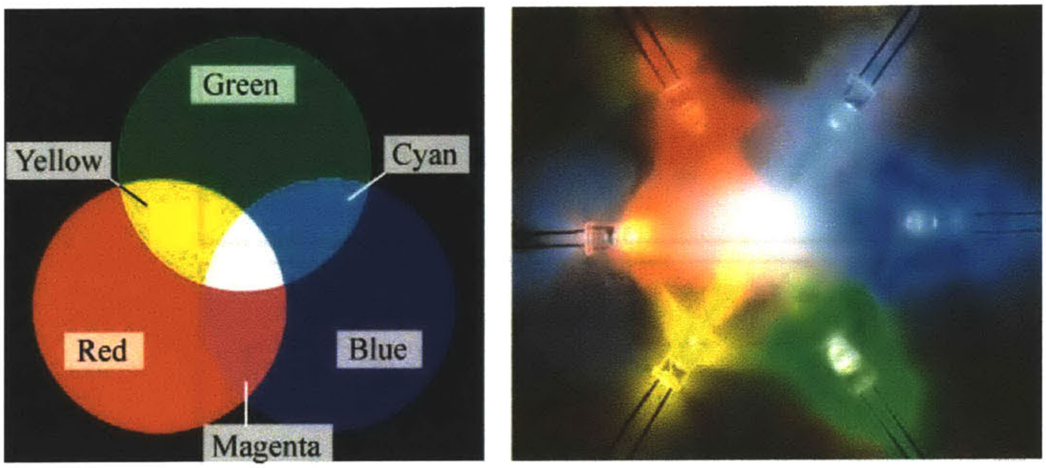


Figure 24 – Schematic of additive color mixing of the three primary colors and additive color missing using LEDs. Data and picture from www.lightemitting.diodes.org.

three primary colors and an additive color mixing using monochromatic LEDs. If the individual colored LEDs are independently controlled, it is possible to vary their intensities, and a full range of different types of white light (or colored light) can be obtained.

From the information given in chapter 2 of this manuscript, when the spectral power distribution of a white light source is given, one can calculate the chromaticity coordinates, color temperature (CCT), color rendering (CRI), and the luminous efficacy of radiation of the lighting system. If two different LED colored lights are additively mixed, the chromaticity of the resultant light must lie on a straight line between the chromaticities of the original lights (CIE, 2004) (figure 25). If more than two lights are additively mixed, the chromaticity of the resultant light must be within the polygon created with the chromaticity coordinates of the component lights, which can also be called the gamut area. The choice of the peak wavelengths for such narrow-band light sources is critical, as the wavelengths determine the chromaticity gamut, the rendering of illuminated objects and the luminous efficiency (www.lightingemittingdiodes.org; Worthey, 2003). Depending on the desired characteristics one can select the appropriate wavelength and number of colored LEDs for the mixture.

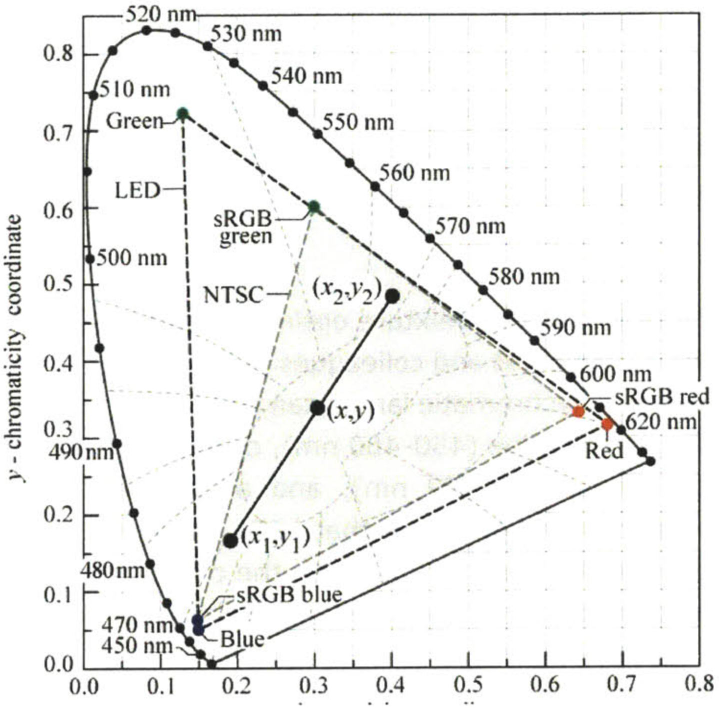


Figure 25 – Principle of color mixing illustrated with two light sources with chromaticity coordinates (x1, y1) and (x2, y2). The resulting color has the coordinates (x, y). Also shown is the triangular area of the chromaticity diagram (color gamut) which results from the additive mixing of a red, green, and blue LED. Data and picture from www.lightemitting.diodes.org.

Previous research (Li et al, 2004; Zukauskas et al, 2001, 2002) using various optimization techniques investigated the performance of the different wavelength combinations for LED sources consisting of two, three, four and five colored LEDs combinations to achieve maximum luminous efficacy and general color rendering. It has been shown that when mixing narrowly peaked wavelengths, the luminous efficacy and color properties are interrelated, as there is a fundamental trade-off between color rendering and luminous efficacy (Thornton, 1971, Narendran, 2002, Ohno, 2004). One of the two quantities can be maximized only at the expense of the other. For example, dichromatic lamps can offer very high luminous efficacies (> 400 lm/W) but result in CRI that are not appropriate for architectural lighting. Tri-chromatic lamps can offer high luminous efficacies (> 300 lm/W) and relatively high CRI (in excess of 80 points) which, at a first glance, seems sufficient for most general-lighting applications. However, such CRI were found to be somewhat deceiving because the high CRI value obtained from the calculations with tri-chromatic lamps did not agree with subjective evaluations (Schanda, 2002; Sándor et al, 2004). Lamps with four and five LEDs were found to provide quasi continuous spectra (Zukauskas, 2001 and 2002), which became important when color rendering is analyzed in more detail (i.e. visual tests with humans).

In theory, it is possible to have each LED color of a mixture optimized for the highest value of color rendering (CRI). Zukauskas and colleagues (2004) also showed that a whole family of optimized polychromatic lamps can be realized by using five groups of colored LEDs, namely blue (450-460 nm), cyan (490-510), green (530-540 nm), yellow-green (560-570 nm), and amber-to-red (600-630 nm). However, it is important to point out that LEDs on such wavelengths cannot currently be found in the market. Currently, the colors of commercially available LEDs are mostly determined by industry standards for video displays and signaling (such as traffic lights), and although theoretical optimizations for the mixtures can be calculated, practical research is done with non-ideal lamps employing industry-predetermined peak wavelengths instead of those required for ideal lamps. This is the case of the LED panels fabricated for this thesis research, and described in chapters 5 and 6 of this manuscript.

4.3. LED, COLOR RENDERING & CURRENT RESEARCH WORK

As explained in Chapter 2, color rendering index, CRI is the only internationally accepted color rendering metric, used as a quantitative evaluation of color rendition capabilities of white light. However, as it was just mentioned in the previous paragraphs, results from CRI investigations for tri-chromatic and tetra-chromatic LED-based white lighting show that the CRI is not a reliable method (Schanda, 2002; Stanikunas et al, 2004; Sándor et al 2004; Bodrogi et al, 2005; Davis & Ohno, 2005). It has been found that the CRIs calculated from eight or fourteen standard color samples yield only a rough estimation, as these color samples do not adequately span the satisfactory range of object colors. This became particularly prominent with light sources with peaked spectral distributions as LEDs. In particular, the perceived and calculated color rendering of LED-based sources was shown to mismatch, and the need to revaluate the method for color rendering calculation is being widely discussed. Discussions and research work for revisions for the CRI have been proposed in the past, based on research with fluorescent light, and more recently, investigating LEDs (Halstead, 1977; Schanda, 1978; Worthey, 1982; Pointer, 1986; Yaguchi et al, 2001; Guo & Houser, 2004; Davis & Ohno, 2005). Different groups are working on developing recommendations to modify the CRI, or to create entirely new methods for color rendering evaluation (Davis & Ohno, 2005; Sándor and Schanda, 2006). However, the general opinion of the lamp manufacturers has been that, before any new method becomes accepted, first the present CRI method should be evaluated using visual experiments.

In view of that demand, and as it becomes clear that CRI is indeed poorly correlated with subjective ratings under LED lighting, psychophysical experiments on color perception under such sources becomes ever more important. A few studies of visual perception under LED lighting explored some preliminary qualitative aspects of color rendering (Raghavan & Narendran, 2002; Shakir & Narendran, 2002). Other more ambitious investigations were successfully implemented and provide quantitative psychophysical results which offer precious information on understanding color perception under poly-chromatic LED light sources (Stanikunas et al, 2004 and 2005; Sándor and Schanda, 2006).

Stanikunas, Zukauskas and their colleagues (2004 and 2005) investigated color perception of forty color samples under illumination with a tungsten lamp and under a quadric-chromatic LED lamp. Their psychophysical experimental set-up contained a viewing booth for the color samples and a computer-driven color monitor. The cabinet was illuminated by either the LED system or by a tungsten lamp. During the experiment, a subject looked at an illuminated color sample within the cabinet and matched it with the color of the stimuli displayed on the monitor. In this way, all the acquired color settings of the monitor were recorded as the perceived chromaticities. Therefore, the changes in the color samples illuminated by the LED versus tungsten lamp were obtained by physical colorimetric calculation comparisons and by psychophysical experiments from the subjective matching of the samples.

It was demonstrated that the yellow-green (440-500 nm) and blue-cyan

(560–580 nm) regions, where both the objective and subjective color distortions were highest, correspond exactly to the area between the spectral peaks of the retinal receptors (Wyszecki & Stiles, 1982), where human sensitivity to spectral variations is highest. The authors suggested that the spectra of quadric-chromatic white LED systems should contain intense and smooth components in the 560–600 nm and 470–500 nm ranges in order to avoid such color distortions. In a way, these observations seemed to contrast with Thornton's theory (previously described in Chapter 3) which explained the high color rendering properties of some tested fluorescent lamps from the fact that their spectral peaks coincided with the three eye sensitivity spectral peaks at 450, 540 and 610 nm (Thornton, 1971). Zukauskas' team suggested that composite white LED light with high subjective rating of illumination, should be optimized with components both at the peaks of the RGB eye's spectral functions and also with in the in-between yellow–green and blue–cyan regions, respectively. They concluded by indicating that further development of quadric-chromatic LED sources depend on solution of the technological issue related with the fabrication of efficient LEDs in the yellow–green spectral region (as the cyan LEDs in the 500-nm range are already available).

Sándor and Schanda performed a series of pilot experiments and found that the color rendering index did not always describe visual color rendering correctly, especially in the case of white LEDs (Sándor et al, 2004; Bodrogi et al, 2005). They then set up a more systematic series of visual color rendering investigations to check if the visual results would find correlation with the current method of calculating color rendering index, and with possible updates of the calculation method (Sándor & Schanda 2006). In this latest work a double booth was constructed to compare reference lamp and test source illuminated color samples. Experiments were conducted using lamps of three values of color temperature. For each level of color temperature it was selected one lamp with a good CIE color rendering index as reference and the other lamps as test sources. The task of the observer was to scale the visual color difference between the corresponding color samples. The task of the experiment was to check whether the visually observed color differences between the corresponding colors in the two booths correlate with one or the other color difference formula.

These visual experiments have shown that the CIE Test Method is not a good predictor of visual perception and that a fundamental re-thinking of the concept of color rendering seems to be appropriate. A method based on calculating color differences provided better correlation between visual and calculated color rendering values. As a result, none of the colorimetric formulae evaluated described the visual color differences well. With increasing correlated color temperature the correlations slightly improve. It was suggested that color rendering properties of a given light source be divided into two major groups. First, if one defines color rendering according to the CIE definition (scaling and averaging color differences between numbers of color samples) and a second one considering color rendering as the maximum realizable number of colors.

4.4. MULTI-CHIP LED FOR LIGHTING: CURRENT CHALLENGES

Although multi-chip LED technology offers many promising features the principal drawback of LED color mixing systems is increased complexity. There are still some key challenges and some critical issues involved in creating a good quality, stable white light source (Narendran, 2001). For example, such systems require multi-chip mounting and need sophisticated optics for blending the individual colors. Also, the color temperature, color rendering and efficiency of LED sources vary with temperature, a major difference from conventional lighting sources (Muthu et al, 2002; Chhajed etal, 2005). LED emission powers decrease exponentially with temperature and the colors obtained by a precise mixing strategy may suffer significant drifts as the ambient temperature of the device increases. For that reason, these systems may require to be equipped with stabilizing feedback circuit for the compensation of optical power variations of the colored LEDs with temperature (Zukauskas et al, 2004).

Another important challenge to be resolved before LED color-mixing systems can be prescribed for general lighting is the tolerance criteria for color temperature and color rendering variation. Currently, traditional white light sources (i.e. fluorescent and incandescent) used in architectural lighting come in a variety of color temperatures and color rendering from factory. Architects define what type of lamp to buy according to the color rendering that will most appropriate for each use, or what color temperature (i.e.

low CCT, "warm" and high CCT, "cool" light) will create visually appealing architectural spaces. The same color variation, if uncontrolled, could become an undesirable feature (Narendran, 2001). This type of concern is much more serious when considering the unprecedented controllability of LED sources. When the prevailing lighting in a room transitions through different qualities of white, it can impact not only the spatial aesthetics, but also how effective and efficiently people's eyes can process the visual information therein. In today's context of exploring the unlimited controllability of LEDs, the main properties of white light – color temperature and color rendering – ought to be carefully studied to ensure safe and appropriate visual conditions. Criteria for human vision tolerances for chromatic differences of different white LED settings should be determined. This is what this thesis research work is mostly concerned with.

CHAPTER 5. PSYCHOPHYSICAL EXPERIMENTS - PHASE 1

5.1. INTRODUCTION

The experiments in Phase 1 are dedicated to investigating how the visual system perceives changes in the spectral components of white illuminants, in particular, to assess human perceptual tolerances to color rendering manipulation. The two fundamental hypothesis were that saturated red color palettes would be the most affected by the type of spectrum manipulation (reducing color rendering by reducing red emission); and that there would be a reduction in visual sensitivity to the observed color distortions when the color changes were not compared side-by-side. The ultimate goal is to assess the visual perception of dynamic modulation of color rendering in architectural settings where it is speculated that the perceived color distortions will be negligible.

This chapter describes two series of double booth experiments (Phase 1A and 1B) where observers evaluated the appearance of twenty four color samples under seven white composite spectra generated by multi-chip LEDs and compared these to a reference source, an incandescent bulb. The color temperature and illuminance of all light spectra were held constant, while each of the LED spectra had a different Color Rendering Index (CRI) varying from highest, Ra = 89 to lowest Ra = 29. The seven LED spectra were presented to the observers in random order in a discrete sequence controlled by a manual switch. In Phase 1A the two different light booths were seen simultaneously, placed on top of a platform side-by-side; and in Phase 1B the booths were seen sequentially, placed in the same two platforms, but this time one on each side of the experimental room. Colorimetric calculations in the CIE 2004 CIELAB color space for the color samples revealed the color differences (ΔE*) between each tested LED spectra and the incandescent bulb. All physical measurements (i.e. product spectra of LED light and reflectance; general and special CRIs, and color differences, ΔE*) were compared with the psychophysical results to verify whether visual observation agreed with the measurements.

It is well known that the red-green contrast is very important in color rendering and that the red component tends to be a key factor in color appearance. The lack of red component shrinks the reproducible color gamut, which in turn tends to make the illuminated scene appear undistinguishable or dull (Worthey, 2003; Ohno, 2004). One specific purpose of these visual tests was to understand how the manipulation of red and yellow emissions from a white LED mixture would affect perception of colors, especially of red and yellow color samples. Understanding that the true color of an object requires a certain reference illuminant in mind, the goal was also to facilitate a preliminary classification of colors that would be most affected (undergo larger perception color distortions compared to color under incandescent) by LED spectra of reduced CR.

The results from these experiments were primarily able to demonstrate: (a) Color-perception differences under seven LED white spectra of different CRIs; (b) Correlation between reduced color rendering and various colors of high and low saturation. In the context of the whole research work, which includes Phase 2, the results from Phase 1 worked as a baseline providing validation of the anticipated premises, such as, that saturated red color palettes would be the most affected by reducing color rendering; and that there would be a reduction in visual sensitivity to the observed color distortions when the color changes were not compared side-by-side.

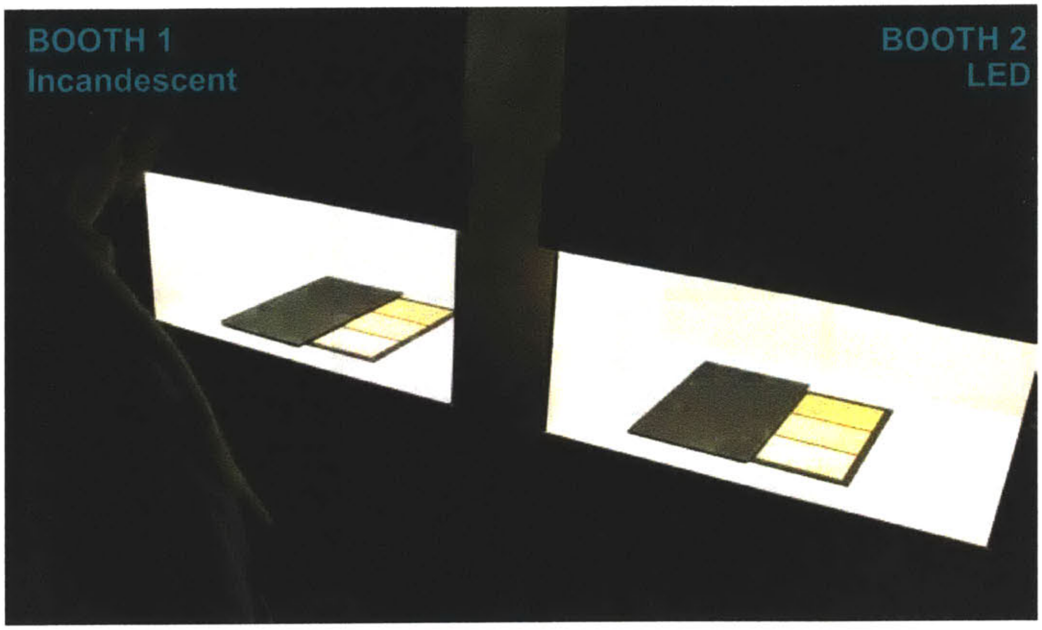


Figure 26 - Subject facing illuminated booth openings and color charts in phase 1A.

5.2. EXPERIMENTAL SET-UP: PHASE 1A

5.2.1. Booths

The experiment was carried out in a dark room containing two identical booths of dimensions 22 × 15 × 28 inches. Booth #1 was equipped with an incandescent bulb and booth #2 was equipped with a LED panel containing Red, Yellow, Green and Blue LEDs (figure 26). The color samples were placed on the floor of each booth. The inside of the booth was painted with light grey matte paint to maintain smooth background illumination.

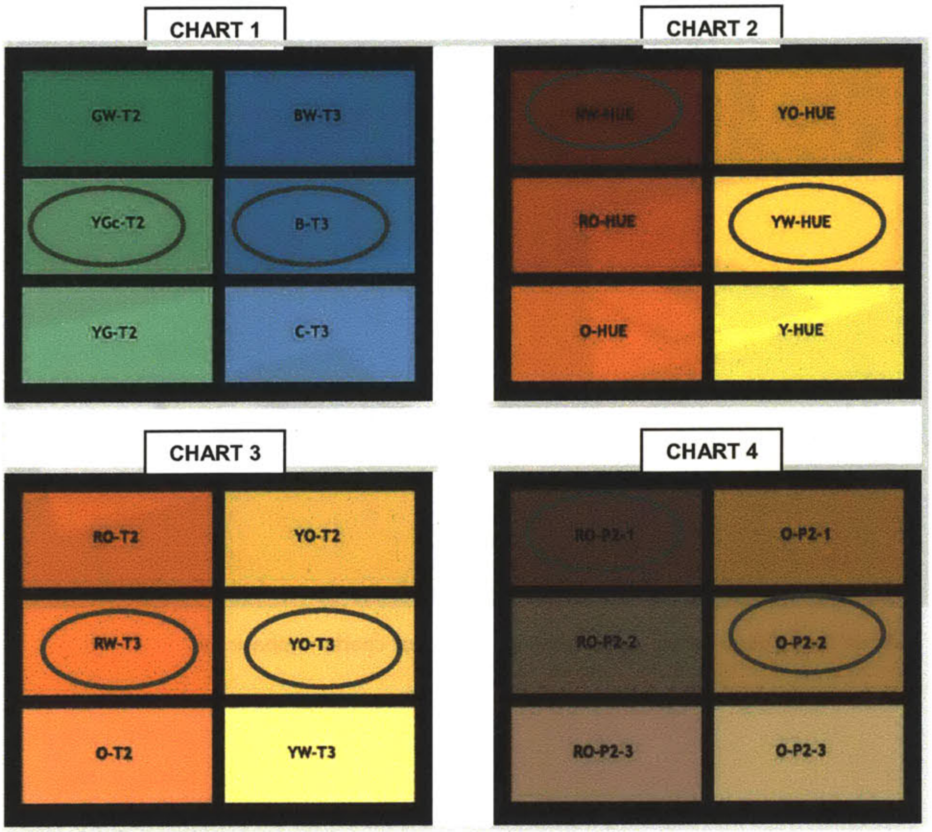


Figure 27 - Color charts used during the experiments. Circled are the eight color samples analyzed.

5.2.2. Color Samples

The color order system used in this study was the Color-Aid system (coloraid.com). Similar to the popular Munsell system (Munsell, 2004), this color system scales colors in hue, saturation and lightness and organizes colors in all regions of this three dimensional color space. Twenty four Color-Aid samples were used in the experiment (namely, GW-T2 , YGc-T2, YG-T2, BW-T3, B-T3, C-T3, RO-T2, RW-T3, O-T2, YO-T2, YO-T3, YW-T3, RW-HUE, RO-HUE, YO-HUE, YW-HUE, Y-HUE, RO-P2-1, RO-P2-2, RO-P2-3, O-P2-1, O-P2-2, O-P2-3). These samples were organized in four color charts (figure 27), and presented to the subjects in groups of three colors (figure 28) so that they placed their judgments, giving individual ratings for each color.

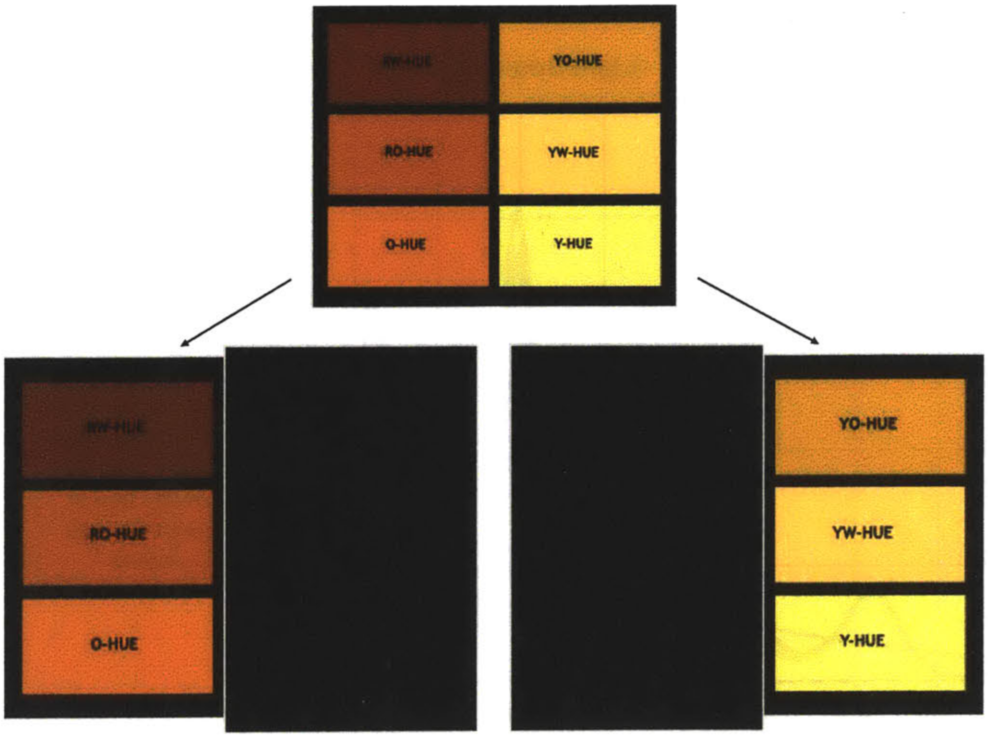
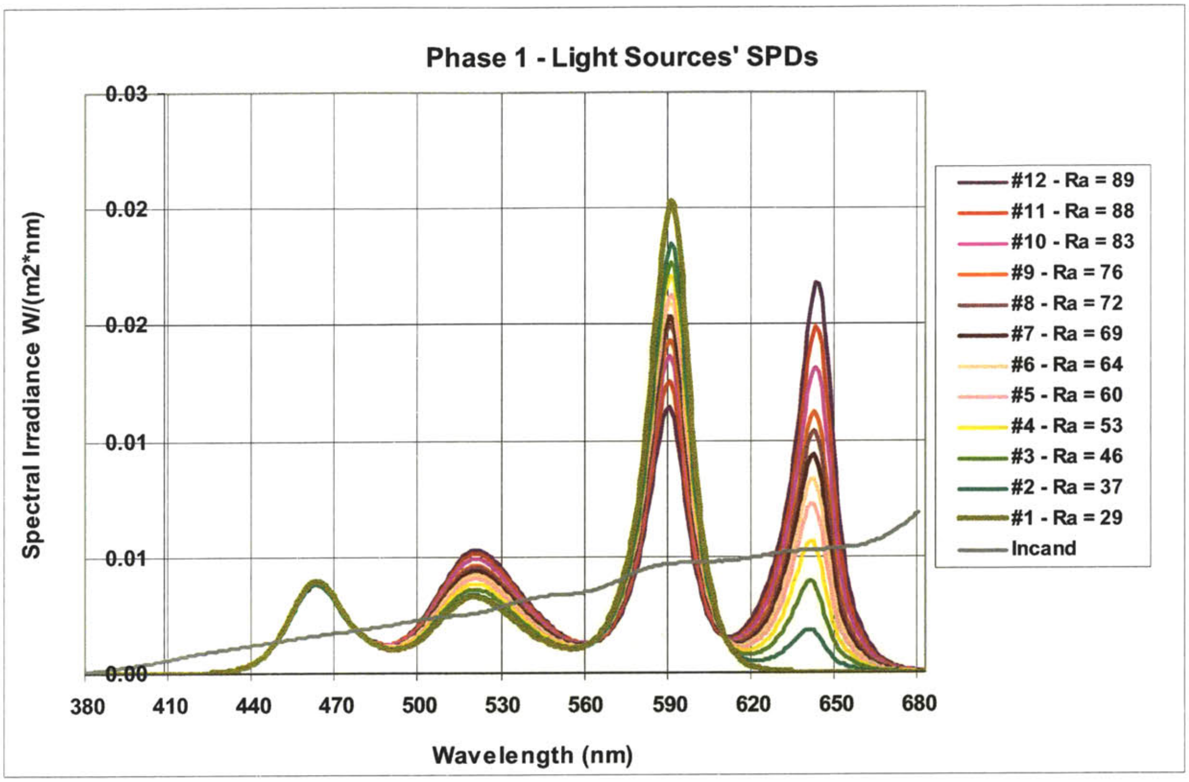


Figure 28 - Example of color chart (chart 3) as it was presented to subjects during experiment.

5.2.3. Light Sources

The four color channels (Red, Yellow, Green & Blue) of the LED panel were individually tuned to produce twelve composite white spectra with different color rendering but same chromaticity and light level of the reference source, an incandescent bulb (graph 1). Correlated color temperature and lumen levels were held constant at approximately 3000 K and 300 lux respectively, while each of the LED white spectra had a different general Color Rendering Index (CRI - Ra) varying from 89 to 28. The incandescent bulb operated in 110 V and was filtered with a ROSCO filter #3206 to slightly raise the original incandescent color temperature.



Graph 1 - Spectra power distribution, SPD, of twelve LED white composite spectra and incandescent bulb. Among these, seven spectra (#2, #3, #4, #5, #6, #9, & #11) were selected to be used during phase 1 experiments.

A small digital controller was built to operate the lighting system in phase 1 (figure 29). It used a PIC microcontroller (Morton, 2005) performing pulse width modulation[1], PWM, to regulate the voltage supplied to each LED color channel individually. The PIC microcontroller was programmed in PIC-assembly code to produce multi-channel PWM with a frequency of 1 KHz and a duty cycle of 1-100 % with 0.5 % resolution. The light settings were programmed for the individual color channels (PWM signals assigning particular Voltages for each channel) and were selected through switches connected to the microcontroller.

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[1] Pulse width modulation (PWM) is a powerful technique for controlling analog circuits with a processor's digital outputs. PWM control works by switching the power supplied to the system on and off very rapidly. The DC voltage is alternated between on (approximately 11V) and zero, giving the system a series of power "kicks". If the switching frequency is high enough, the system operates at a steady speed. By adjusting the duty cycle of the signal, one is basically modulating the width of the pulse (the 'PWM') ie, the time fraction it is "on". By switching voltage to the load on and off with the appropriate duty cycle, the output brings the voltage to the desired level. This way the average power can be varied, and hence the device (in our case, the lighting intensity in the lighting channel) is controlled.

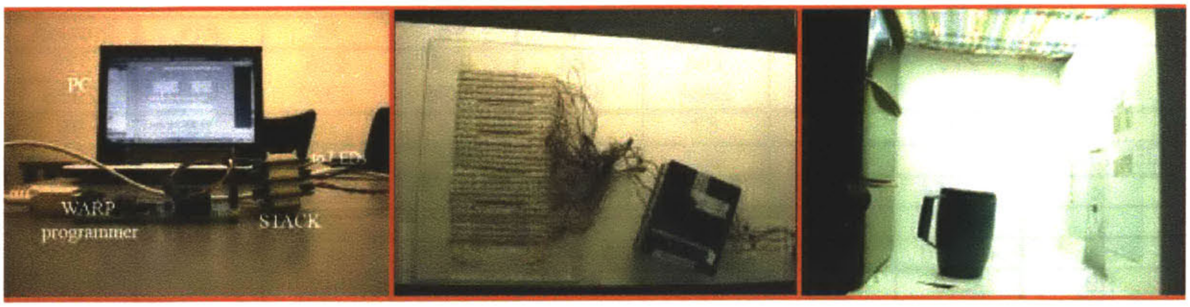

Figure 29 – Lighting system used in phase 1 experiments: LED panel and controller.

Using one set of dominant wavelengths -- 633 nm (Red), 587 nm (Yellow), 525 nm (Green) and 470 nm (Blue) commercially available from Osram Sylvania[2] -- a succession of color-mixing calculations was performed to craft a list of white composite spectra that would mimic the chromaticity and lumen level of the incandescent bulb. In order to maintain the chromaticity and lumen level and to vary the color rendering, the general color mixing approach used was to change the ratio of red to yellow, keep the blue component fixed and make minor adjustments to green. First, a spectrum with high color rendering (and strong red energy), was created namely spectrum #12, and then the other spectra of reduced color rendering were sequentially created by gradually reducing the red component while increasing the yellow component. The lowest color rendering spectrum, spectrum #1, has no red and very high yellow emission. The main objective of this particular approach was to compensate for the reduced red emission with yellow emission to attain higher efficacy sources. All the balance against the blue and green spectral components is obtained with the yellow emission, and consequently spectrum #1 presents very poor rendering, but high efficacy. For all spectra the blue component was held fixed while minor adjustments were made to the green mainly to keep a constant chromaticity and illuminance level. Of the twelve spectra created, seven were selected for the psychophysical experiment. Table 4 summarizes the results from the measurements of these seven LED spectra and the incandescent, showing general CRI–Ra, special CRI, CCT (K), LER (lm/W), and other key parameters.

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[2] Osram Sylvania LINEARlight LED modules Red (LINEAR/633/OS/LM01A/S1), Yellow (LINEAR/587/OS/LM01A/Y2), Green (LINEAR/525/OS/LM01A/T2) and Blue (LINEAR/470/OS/LM01A/B1).

	#2	#3	#4	#5	#6	#9	#11	Incand.
lux	279	280	284	284	287	286	289	275
CCT	3001	2992	2984	3007	2996	3022	3043	2968
CRI	**37**	**46**	**53**	**60**	**64**	**76**	**88**	**98**
LER (lm/W)	**415**	**398**	**385**	**373**	**366**	**345**	**322**	
x	0.4354	0.4358	0.4364	0.4351	0.4358	0.4341	0.4330	0.4375
y	0.4011	0.4007	0.4010	0.4011	0.4014	0.4009	0.4012	0.4014
u-v	0.0010	0.0012	0.0011	0.0009	0.0009	0.0009	0.0006	0.0012
R9	**-269**	**-206**	**-158**	**-112**	**-85**	**-12**	**68**	**90**

Table 4 - Summarized results for seven composite white spectra and incandescent used in visual tests.

5.2.4. Product Spectra and Colorimetric Color Differences ΔE*

Graphs 2, 3 and 4 show plots with the spectral reflectance of eight selected color samples and the "product spectra", generated by multiplying each of the spectral reflectance[3] by the seven SPDs of the light sources used in the experiment. The product spectra represent the color balance reflected from the color samples to the subjects' eyes under each light source from within the booths during the experiment. In order to make the analysis of the graphs more tangible we included tables containing the calculated colorimetric color difference, ΔE*, for the color samples under each LED spectra. The colorimetric color difference, ΔE*, is a number denoting the difference between the reflected of the color sample under the reference source (filtered incandescent bulb) and under each tested LED source. The calculations for ΔE*, followed CIE document CIE 15:2004 (CIE, 2004), which uses the CIELAB object color space. These physical measurements will later be compared with the psychophysical results to verify whether visual observation agreed with the measurements.

The title of each plot on figures 2, 3 and 4 display the ColorAid name of the correspondent color sample. In the plots, the blue dashed line is the sample's spectral reflectance plotted against wavelength. The grey line is light reflected

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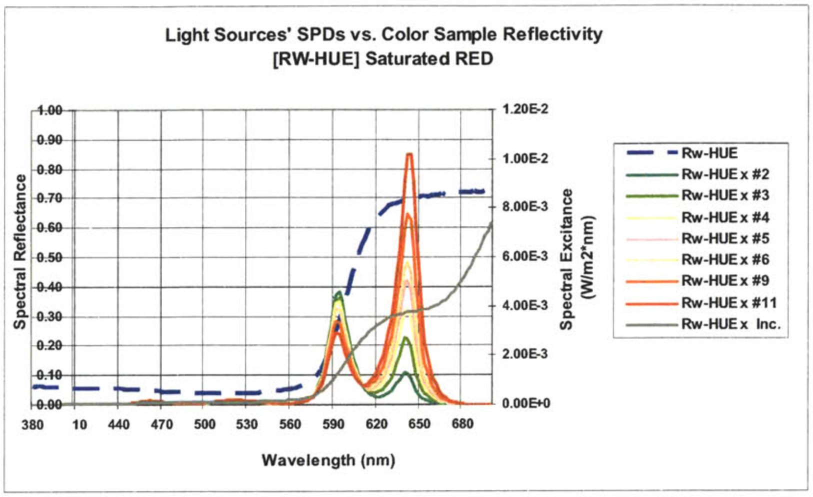
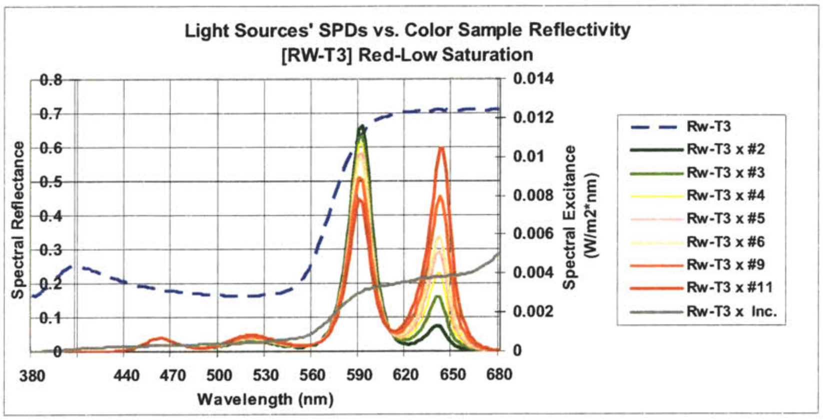
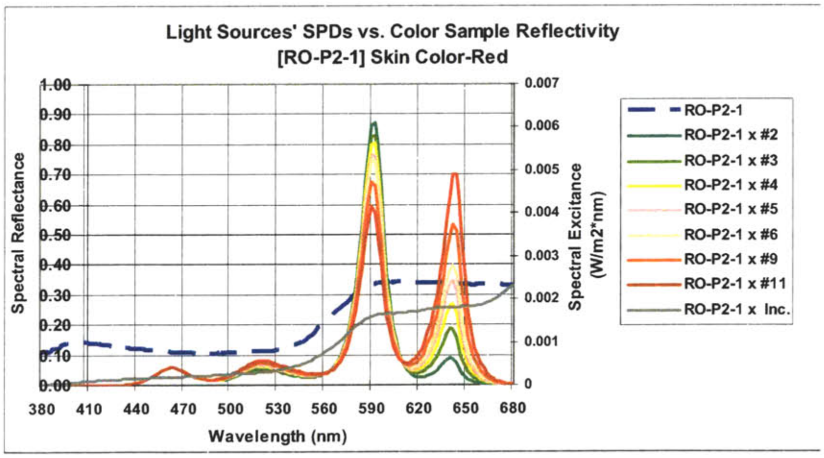
[3] The spectral reflectance of the color samples were measured using a Photo Research, Inc. PR-705 Spectra Scan tele-spectroradiometer. The reflectance spectra were obtained by comparing the measured spectral radiance to that obtained from a barium sulfate plaque placed at the location of the color samples.



Color Sample	ΔE*
RW-HUE - inc.	x #2 = 24.00
RW-HUE - inc.	x #3 = 20.82
RW-HUE - inc.	x #4 = 18.14
RW-HUE - inc.	x #5 = 15.12
RW-HUE - inc.	x #6 = 13.55
RW-HUE - inc.	x #9 = 8.42
RW-HUE - inc.	x #11 = 2.99



Color Sample	ΔE*
RW-T3 - inc.	x #2 = 14.25
RW-T3 - inc.	x #3 = 12.25
RW-T3 - inc.	x #4 = 10.58
RW-T3 - inc.	x #5 = 8.63
RW-T3 - inc.	x #6 = 7.76
RW-T3 - inc.	x #9 = 5.24
RW-T3 - inc.	x #11 = 5.07



Color Sample	ΔE*
RO-P2-1 - inc.	x #2 = 7.03
RO-P2-1 - inc.	x #3 = 5.85
RO-P2-1 - inc.	x #4 = 4.91
RO-P2-1 - inc.	x #5 = 3.90
RO-P2-1 - inc.	x #6 = 3.52
RO-P2-1 - inc.	x #9 = 3.02
RO-P2-1 - inc.	x #11 = 4.42

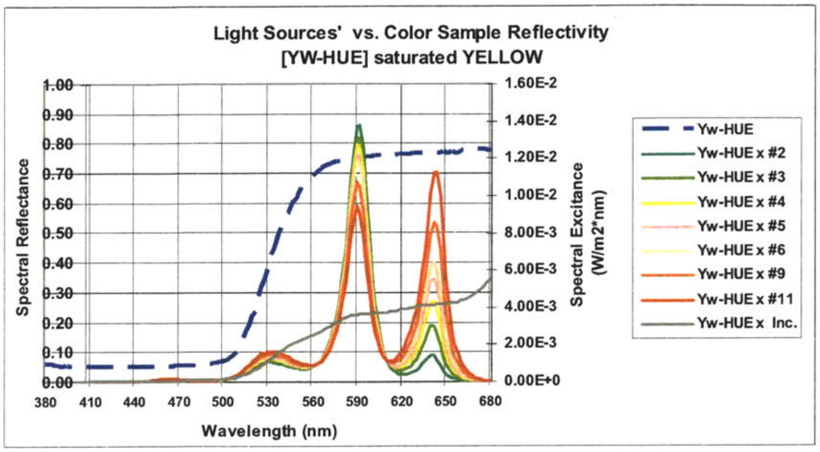
Graph 2 - Spectral reflectance of RED color samples (RW-HUE, RW-T3, RO-P2-1) against SPD of product spectra and ΔE* table.

from the sample under the incandescent lamp. The colored solid lines are the light reflected from the sample under the various LED spectra. The plots show how the individual colored emission from the LED spectra interacts with the reflectivity of the color samples and we can compare the change of the red to yellow ratio from sample to sample. For example, LED spectra #11, represented by a red solid line (with the highest amount of red emission and highest CRI), has always the highest energy in the red region and the lowest energy in the yellow region.

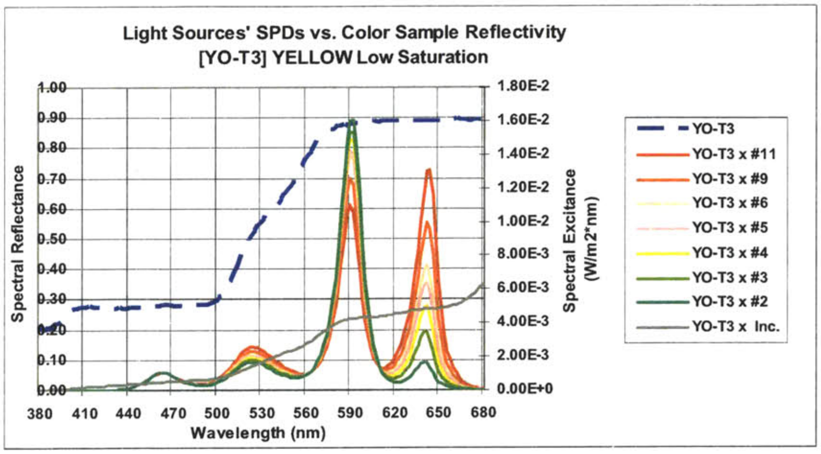
Although all the seven selected spectra are relevant for this investigation, the attention of this analysis will be primarily focused on spectra #4, #5, and #6 which represent the middle range CRIs among the seven spectra. This is because it is fairly certain that the high CRI spectra such as #9 and #11 will generally provide acceptable rendering for the observers, and that the very low CRI spectra such as #2, and #3 will generally provide poor rendering, but there is particular interest about the results for spectra #4, #5, and #6 to see how the reduced CRI influenced the visual appearance of the samples.

Some trends were observed when comparing the reflectivity and SPDs from the plots with the ΔE* values from the tables. In this study, lower ΔE* values will correspond to 'most incandescent like', and therefore most of these trends will be related to the fact that the spectrum of the incandescent bulb is continuous in nature, and so has energy at all wavelengths to offer to the reflectivity of any color sample, but the LED system consists of narrow band emissions that can be very specific in rendering certain color samples. Therefore a critical part of this analysis is to carefully examine the relationship between the spectral characteristics of the illuminants and the reflectivity of the sample, shown in these plots.

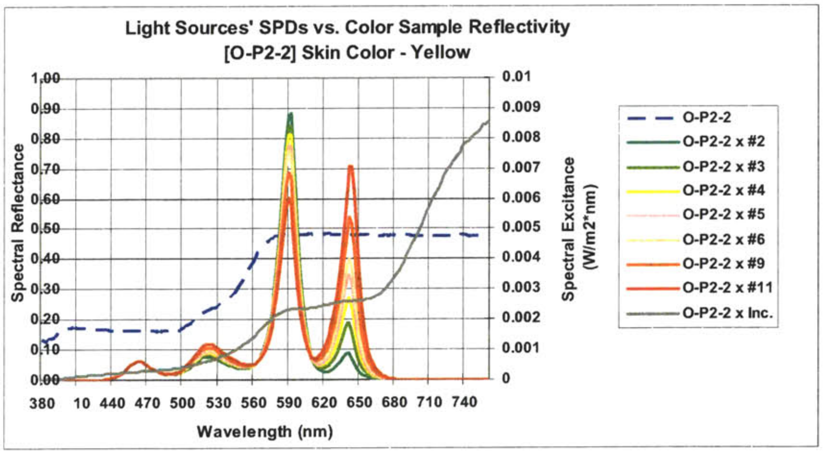
The plots and tables in graph 2 show that red samples RW-HUE and RW-T3, have the highest values of ΔE* compared to the other samples, and the values were even higher for RW-HUE, the more saturated red. One explanation for this is the fact that red color samples (particularly saturated ones) reflect mainly red light, and in order to render them properly, the illuminant depends on the amount of red emission of its spectral composition. This plot shows that the incandescent spectrum (the product spectrum of this sample with the incandescent bulb) has more energy on the red than on the yellow region. When the LED spectra (product spectra with LED) present a similar proportion



Color Sample	ΔE*
YW-HUE - inc.	x #2 = 1.79
YW-HUE - inc.	x #3 = .89
YW-HUE - inc.	x #4 = 1.38
YW-HUE - inc.	x #5 = 2.63
YW-HUE - inc.	x #6 = 3.31
YW-HUE - inc.	x #9 = 5.62
YW-HUE - inc.	x #11 = 8.44



Color Sample	ΔE*
YO-T3 - inc.	x #2 = 2.60
YO-T3 - inc.	x #3 = 1.69
YO-T3 - inc.	x #4 = 1.14
YO-T3 - inc.	x #5 = 1.24
YO-T3 - inc.	x #6 = 1.60
YO-T3 - inc.	x #9 = 3.15
YO-T3 - inc.	x #11 = 5.21



Color Sample	ΔE*
O-P2-2 - inc.	x #2 = 3.37
O-P2-2 - inc.	x #3 = 2.44
O-P2-2 - inc.	x #4 = 1.8
O-P2-2 - inc.	x #5 = 1.49
O-P2-2 - inc.	x #6 = 1.63
O-P2-2 - inc.	x #9 = 2.91
O-P2-2 - inc.	x #11 = 4.94

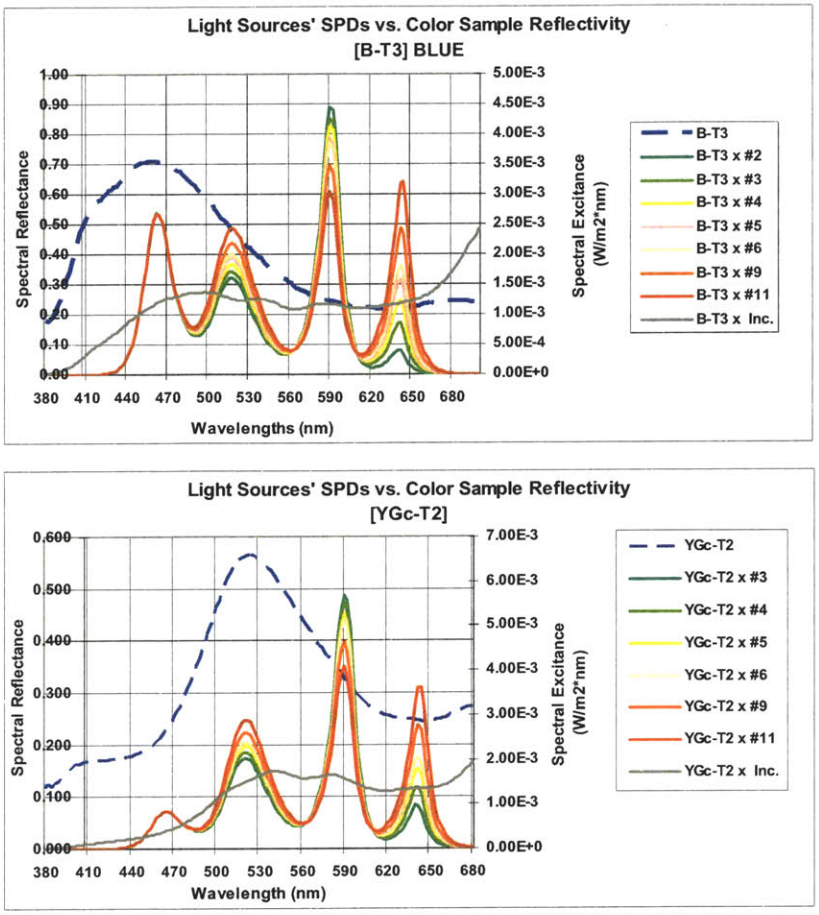
Graph 3 - Spectral reflectance of YELLOW color samples (YW-HUE, YO-T3, O-P2-1) against SPD of product spectra and ΔE* table.

of red and yellow emissions, such as spectra #11, it will tend to generate lower ΔE* values compared to when the red to yellow ratio is inverted, such as in spectra #2. For that reason, it makes sense to see that the ΔE* values increased substantially as we gradually subtracted red light emission from our LED lamp. Also to be noted is the sharp cut-off of the reflectivity of the saturated red sample RW-HUE on the yellow region, which shows that this sample reflects little of the yellow emission from the LED illuminants. As a result, the LED spectra with high yellow and low red emission (such as #2, #3, #4, #5 and #6) have very high ΔE*, and spectra #11, with high energy in red, has very low ΔE*.

The red samples of lower saturation, namely RW-T3 and RO-P2-1, show similar profiles, but lower ΔE* because they are less saturated and therefore reflect also yellow wavelengths. For the blue sample, B-T3 we see in graph 4 that the ΔE* values were much lower. This can be explained because the blue color sample, like the saturated red, is very selective in reflecting wavelengths. It reflects mostly blue light and therefore the changes in the yellow and red emissions did not generate big color differences for this sample. Looking at the reflectance curve of this sample we see that it is low in the red and yellow regions (little red or yellow light reflected) and it is flat (similar amounts of either emissions reflected), which deemphasizes the effect of changing red and yellow emissions of the LED spectra. We can also see that the blue emission from the LED lamp was held fixed for all spectra, which may be another reason for the lower ΔE* values if compared to the red or green sample.

The green sample YGc-T2, also portrayed in graph 4, shows much higher ΔE* values than the blue one, and a possible explanation for this can be found when looking at the green emission from the LED spectra in relation to the reflectivity curve of this sample. The green emission varies considerably among the spectra, following the change of the red to yellow ratio. Another reason may also be that the reflectivity of the green sample is higher in the yellow than in the red region, which makes the rendering ability of the spectra more dependent on the red to yellow ratio.

Graph 3 shows product spectra plots and ΔE* tables for yellow samples YW-HUE, YO-T3 and O-P2-2, we see that for these samples the ΔE* values are much lower compared to all other samples. This can be explained by the



Color Sample	ΔE*
B-T3 - inc.	x #2 = 3.95
B-T3 - inc.	x #3 = 3.10
B-T3 - inc.	x #4 = 2.53
B-T3 - inc.	x #5 = 2.15
B-T3 - inc.	x #6 = 2.18
B-T3 - inc.	x #9 = 2.90
B-T3 - inc.	x #11 = 4.52

Color Sample	ΔE*
YGc-T2 - inc.	x #2 = 8.67
YGc-T2 - inc.	x #3 = 7.53
YGc-T2 - inc.	x #4 = 6.63
YGc-T2 - inc.	x #5 = 5.62
YGc-T2 - inc.	x #6 = 5.21
YGc-T2 - inc.	x #9 = 4.06
YGc-T2 - inc.	x #11 = 3.97

Graph 4 - Spectral reflectance of BLUE (B-T3) and GREEN (YGc-T2) color samples against SPD of product spectra and ΔE* table.

fact that in almost all our LED spectra, except for spectra #9 and #11, we have vast quantities of yellow emission; and this yellow emission was well balanced with the yellow wavelengths from the incandescent bulb. Another trend observed was that, for the saturated yellow sample, YW-HUE, the ΔE* was higher than for the others. This is shown in the plots and can be explained because the more saturated the color, the less will it reflect other wavelengths. The saturated yellow sample reflected modest amounts of green and almost no blue light from the LED spectra, which emphasized the importance of the red and yellow emissions, and the contrast with the incandescent spectrum. That is probably why we see that this sample obtained higher ΔE*.

Another important trend was noticed for the yellow samples. We saw that for the red, green and blue color samples, the higher the yellow emission in our

LED spectra, the lower was the CRI and the higher the ΔE* values. Therefore an increase in yellow emission corresponded to a decrease in rendering quality of the LED spectra, and this was confirmed by the ΔE* calculations and by the visual experiments. But for the yellow samples, the higher the yellow emission from the LED spectra, the better was the color rendering, in spite of the reduced CRI and increased ΔE* values. For example, in the yellow samples there was a decrease of the ΔE* values from spectrum #11 to spectrum #2, hence, ΔE* values decreased as CRI increased. This can once again be explained because a sample of high yellow reflectivity will need considerable amount of yellow emission from the illuminant, and as mentioned before, the yellow emission was progressively increased from spectra #11 to #2. The best LED spectra for the yellow samples (or lowest ΔE*) are not the ones with high CRI, but rather the ones with a good proportion of yellow emission that will be compatible with the yellow energy from the incandescent. Spectra #11, with very little yellow emission, had much higher ΔE* values.

5.3. PSYCHOPHYSICAL EXPERIMENT'S PROCEDURE: PHASE 1A

Ten subjects (six male and four female) with normal color vision participated in the experiment. During the experiment, one subject sat twenty four inches away from the booths in the center line between booths. Each subject directly looked at the identical set illuminated color samples, one within each booth and then placed their judgment on the comparison. The LED tested sources were rated with respect to the incandescent reference source in terms of the difference in appearance between color samples on a four-point semantic scale. Subjects were instructed to mark a questionnaire which asked if the color sample in one booth looked "same", "just noticeably different", "different" or "very different" compared to the color sample in the other booth. The procedure was repeated for a set of twenty four color samples (four charts with six colors each) for all seven LED test spectra. The observers looked at three colors of same hue and different saturation at the same time as these were located at one side of the chart (one side of the chart, was exposed while the other side was blocked) but judged each color individually. The seven different test spectra were sequenced in random order. In between sample charts the subjects remained seated in the same place but were asked to turn around and look at a dark surface wall for approximately 1 minute.

Figure 30 - Subject facing illuminated booth openings and color charts in phase 1B.

5.4. PSYCHOPHYSICAL EXPERIMENT'S PROCEDURE: PHASE 1B

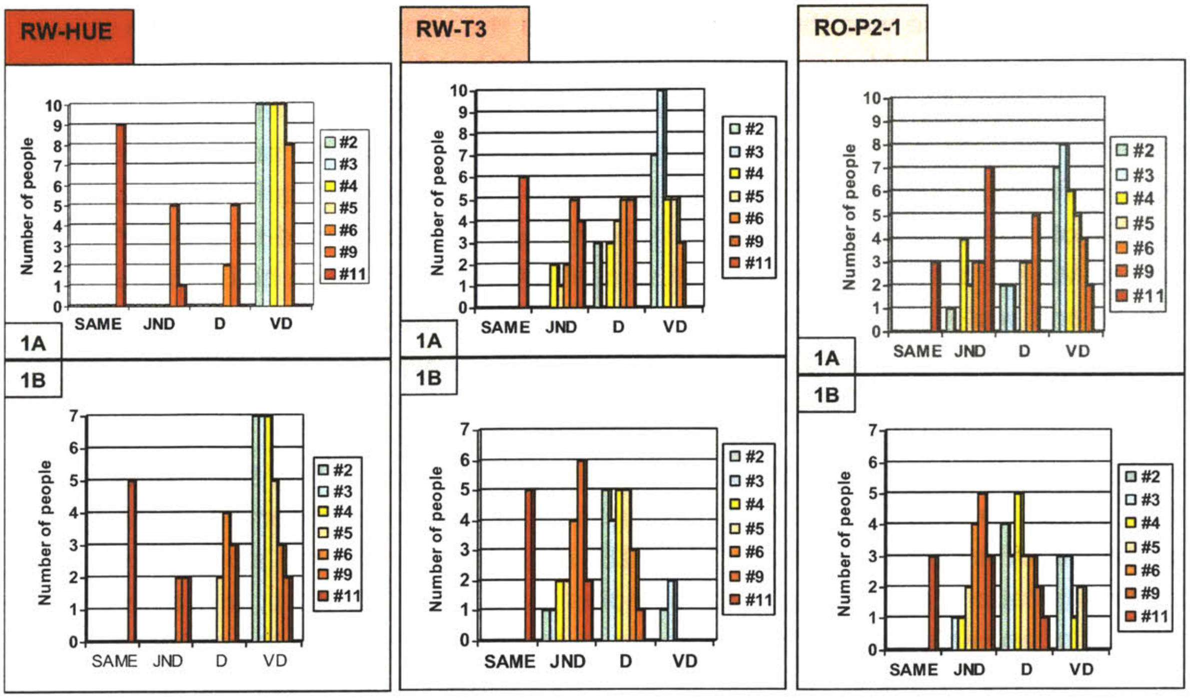
The only changes from phase 1A to phase 1B were in regards to the positioning of the booth and the instructions to the observers. The light sources, product spectra and colorimetric color differences ΔE* are identical of phase 1A, and the experiment was carried out in the same dark room as in Phase 1A, using the same two identical booths. The only difference is that in Phase 1B the booths were placed in opposite sides of the room facing each other, instead of side-by-side. The observers had booth 1 (incandescent) on their right hand side and booth 2 (LED) on their left hand side (figure 30).

Seven subjects (four male and three female) with normal color vision participated in the experiment. During each section of the experiment, one subject sat in between the two booths, twenty four inches away form each booth. Two identical color samples were placed one in each booth, and the subject was instructed to look at the sample in one booth first and then look at its pair sample in the other booth and then place their judgments on the comparison. They were free to look at the two samples as many times as they needed before they marked their questionnaires. The LED tested sources were rated with respect to the reference source in terms of the difference in appearance between color samples on a four-point semantic scale. Subjects were instructed to mark a questionnaire which asked if the color sample in one booth looked "same", "just noticeably different", "different" or "very different" compared to the color sample in the other booth. The procedure was repeated for a set of twenty four color samples (four charts with six colors each) for all seven LED test spectra. Like in Phase 1A, the seven different LED spectra were presented in random order in a discrete sequence. In between samples the subjects remained in the room and were asked to turn to a dark wall and look at that dark surface for approximately 1 minute.

5.5. COMBINED RESULTS AND ANALYSIS FROM EXPERIMENTS IN PHASES 1A AND 1B

The results from Phase 1A and Phase 1B were combined and grouped by color (sets of red, yellow and blue/green samples in graphs 5, 6 and 7 consecutively) in order to facilitate the experimental analysis. The ΔE* values were used as a physical reference and the analysis were focused on the mid-range CRI spectra, namely spectra #4, #5, and #6. The bar charts on graphs 5, 6 and 7 show the number of responses (minimum of 0 and maximum of 10 subjects) on the abscissa and the types of responses ('SAME', 'JND' - Just noticeable difference, 'D'-Different, 'VD'-Very different) on the ordinate; the legend containing representation for the seven selected spectra. Colorimetric calculations in the CIE 2004 CIELAB color space for the twenty four color samples used in the experiment revealed the color differences (designated as ΔE*) between each color sample and its identical pair when one was illuminated by the test LED spectra and the other by the incandescent bulb. The calculated color differences (or ΔE* values) are displayed under the bar charts to be compared to the visual tests' results.

The analysis of the data from the psychophysical experiment helped us understand what magnitude of ΔE* constitutes a significant color difference for each color sample. We see that for the red colors, the ΔE* values ranging from 3 to 4 were said to be 'just noticeably different'; ΔE* from 4 to 9 were considered 'different' or 'very different'; and ΔE* above 9 were unanimously judged as 'very different'. As expected, for the yellow sample ΔE* values had the opposite logic, ΔE* between 2 and 3 were judged to "look the same"



Color Sample	ΔE*
RW-T3 - inc.	x #2 = 14.25
RW-T3 - inc.	x #3 = 12.25
RW-T3 - inc.	x #4 = 10.58
RW-T3 - inc.	x #5 = 8.63
RW-T3 - inc.	x #6 = 7.76
RW-T3 - inc.	x #9 = 5.24
RW-T3 - inc.	x #11 = 5.07

Color Sample	ΔE*
RW-HUE - inc.	x #2 = 24.00
RW-HUE - inc.	x #3 = 20.82
RW-HUE - inc.	x #4 = 18.14
RW-HUE - inc.	x #5 = 15.12
RW-HUE - inc.	x #6 = 13.55
RW-HUE - inc.	x #9 = 8.42
RW-HUE - inc.	x #11 = 2.99

Color Sample	ΔE*
RO-P2-1 - inc.	x #2 = 7.03
RO-P2-1 - inc.	x #3 = 5.85
RO-P2-1 - inc.	x #4 = 4.91
RO-P2-1 - inc.	x #5 = 3.90
RO-P2-1 - inc.	x #6 = 3.52
RO-P2-1 - inc.	x #9 = 3.02
RO-P2-1 - inc.	x #11 = 4.42

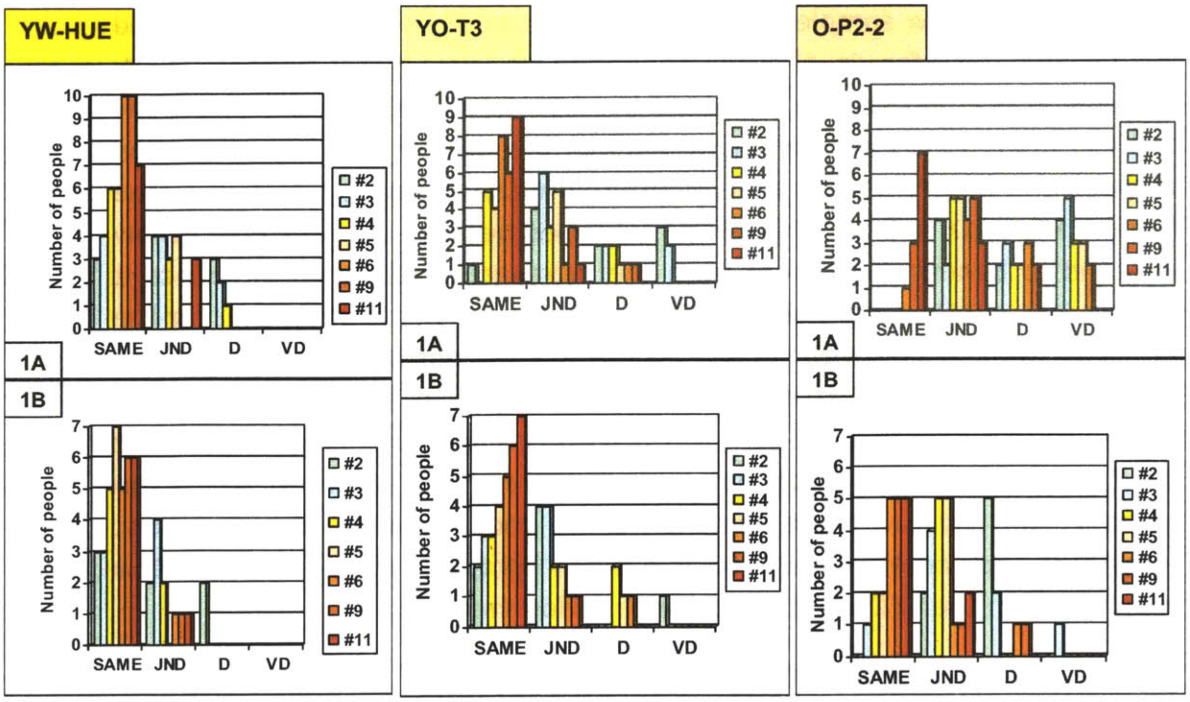
Graph 5 - Calculated color differences ΔE* and subject ratings for RED color samples in Phase 1A and 1B.

and lower values had responses varying from "just noticeably different" to "very different". For the blue samples, ΔE* values above 4 were said to be "different", ΔE* values between 2 and 4 varied from "look the same" to "just noticeably different". For the green sample, ΔE* above 7 were judged as "different", whereas ΔE* ranging from 3 to 6 were said to "look the same" or "just noticeably different".

For the red samples in graph 5 the results plotted on the charts were consistent with the ΔE* calculated for these colors: the bigger the ΔE* value, the more noticeable was the color difference to the observers. For the three red samples analyzed here, the ΔE* values calculated from spectra #11 (rich in red energy) were the lowest; and among the seven LED spectra, none got rated as "look the same", except for spectra #11. For these red samples the color differences were more strongly perceived by the observers for the red sample of higher saturation (RW-HUE), which was also confirmed by the ΔE* values. We see that the saturated red sample RW-HUE, got much higher delta values and was judged to be "very different"; and that the less saturated samples, RW-T3 and RO-P2-1, got lower ΔE* values and received ratings as "different" or even "just noticeably different".

Looking carefully at the charts for the red samples and comparing the results from Phase 1A with Phase 1B, a gradual improvement was observed of the perceived difference from Phase 1A to 1B, especially for the red samples of lower saturation. For example, for samples RW-T3 and RO-P2-1, a greater amount of people answered "VD" in Phase 1A than in Phase 1B; as the majority of the answers for phase 1B were "D" or "JND". These results confirmed what could have been expected from our intuition, as it is well known that the more saturated the color the more selective will it be in reflecting wavelengths. The saturated red sample reflects mainly red light and so it makes sense that as we subtracted red light components from our LED spectra, the observers would readily discern this. On the other hand, the less saturated red samples reflected more yellow light, and then the yellow emission compensated for some lack of red. This was clearly confirmed by the visual appraisal when these spectra were considered 'different' or even 'Just Noticeably Different', as opposed to "very different" for the saturated red.

The charts with the yellow samples (graph 6), show that these results were less intuitive. In respect to the ΔE* values, a pattern can be observed for all three yellow samples: different from the red samples results, the ΔE* values obtained from calculations with mid-range CRI spectra were lower than ΔE* values obtained from the low range or even from the high range CRI spectra. Spectra # 9 and #11 (with highest CRI), for instance, consistently present very high ΔE* values for all three yellow samples, superior to the ΔE* values from the mid-range and even low CRI range spectra. This can be explained by the fact that the high CRI spectra have much reduced yellow energy in their spectrum (as we progressively removed red from the highest to lowest



Color Sample	ΔE*
YW-HUE - inc.	x #2 = 1.79
YW-HUE - inc.	x #3 = .89
YW-HUE - inc.	x #4 = 1.38
YW-HUE - inc.	x #5 = 2.63
YW-HUE - inc.	x #6 = 3.31
YW-HUE - inc.	x #9 = 5.62
YW-HUE - inc.	x #11 = 8.44

Color Sample	ΔE*
YO-T3 - inc.	x #2 = 2.60
YO-T3 - inc.	x #3 = 1.69
YO-T3 - inc.	x #4 = 1.14
YO-T3 - inc.	x #5 = 1.24
YO-T3 - inc.	x #6 = 1.60
YO-T3 - inc.	x #9 = 3.15
YO-T3 - inc.	x #11 = 5.21

Color Sample	ΔE*
O-P2-2 - inc.	x #2 = 3.37
O-P2-2 - inc.	x #3 = 2.44
O-P2-2 - inc.	x #4 = 1.8
O-P2-2 - inc.	x #5 = 1.49
O-P2-2 - inc.	x #6 = 1.63
O-P2-2 - inc.	x #9 = 2.91
O-P2-2 - inc.	x #11 = 4.94

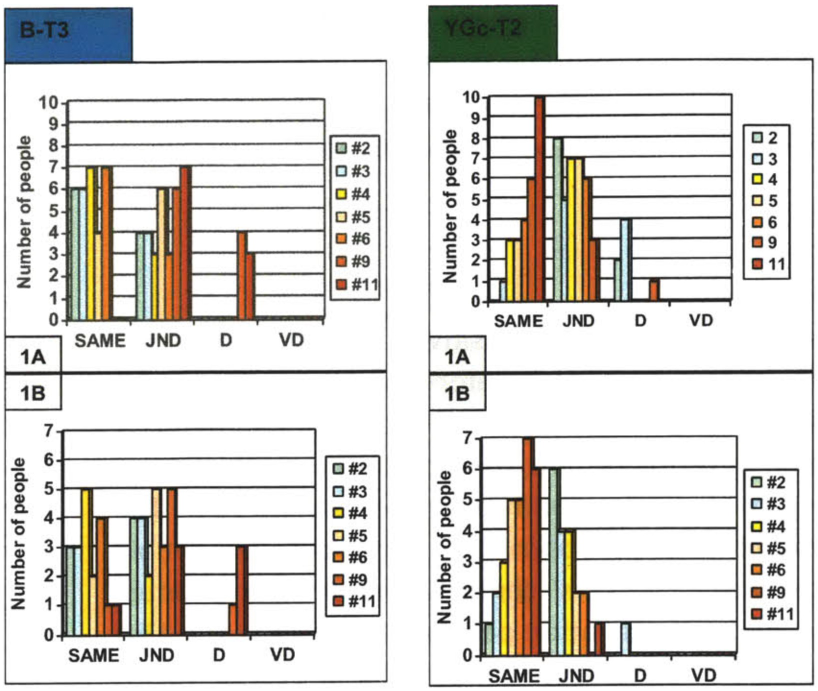
Graph 7 - Calculated color differences ΔE* and subject ratings for YELLOW color samples in Phase 1A and 1B.

CRI spectra, we progressively add yellow and vice-versa), in comparison with spectra with lower CRI, which obviously affected the ΔE* values for the yellow samples.

If the analysis is focused on the mid-range CRI spectra, we can see that, contrary to the red samples, the higher the ΔE* values (progressively raising from YW-HUE to O-P2-2 to YO-T3), the less noticeable was the color difference to the observers. One possible explanation for this comes from the fact that, for yellow samples, wealth of yellow emission should be expected to be a good thing for visual observation, and we know that a higher a yellow emission in our LED spectra, elevated the ΔE* values. The charts also show that the more saturated the yellow sample, the weaker was the correlation between the observers' experience and the measured ΔE*, which was true for both Phase 1A and 1B. This can be explained because the saturated yellow will tend to benefit even more from the increase in yellow energy since it reflects less of other wavelengths. For example, the charts show that for the saturated sample YW-HUE, subjects practically did not notice any difference between the incandescent and the LED spectra, even though this was the yellow sample with highest ΔE*. On the other hand, the samples of lower saturation were judged to be 'different' and even 'very different', which can be explained because these samples reflect good amounts of red, yellow, some blue and sometimes appreciable green light, and therefore the yellow emission from the LED spectra was less predominant.

Another way to see the influence of the saturation on the visual appraisal is when a comparison is made between the performance of spectra #2 and #3 (highest in yellow emission) amongst the three different yellow samples. The charts show that for the saturated sample, most subjects answered "just noticeably different" under these spectra. For less saturated yellow samples, the charts show that spectra #2 and #3 performed considerably worse. Once again comparing results from Phase 1A and 1B it is a noticeable change in the way observers reacted, and that is especially true to the skin-tone yellow, sample O-P2-2. For this particular sample, just one person answered "VD", and very few "D" which is a big contrast with Phase 1A.

Graph 7 shows the charts for the blue and green color samples. In terms of calculated color differences the blue sample is clearly less affected by the CRI modulation than the green sample, as the ΔE* values are much lower, except for spectra #11. This is confirmed by the results from the visual tests which show clearly that most reduced CRI spectra did not affect the visual perception of this sample, and that the two spectra with higher CRI (#11 and #9) were the ones with week visual performance. One explanation for this can be that a blue sample reflects mostly blue light and consequently changes in the yellow and red emissions would not be expected to be registered by the observers.



Color Sample	ΔE*
B-T3 - inc.	x #2 = 3.95
B-T3 - inc.	x #3 = 3.10
B-T3 - inc.	x #4 = 2.53
B-T3 - inc.	x #5 = 2.15
B-T3 - inc.	x #6 = 2.18
B-T3 - inc.	x #9 = 2.90
B-T3 - inc.	x #11 = 4.52

Color Sample	ΔE*
YGc-T2 - inc.	x #2 = 8.67
YGc-T2 - inc.	x #3 = 7.53
YGc-T2 - inc.	x #4 = 6.63
YGc-T2 - inc.	x #5 = 5.62
YGc-T2 - inc.	x #6 = 5.21
YGc-T2 - inc.	x #9 = 4.06
YGc-T2 - inc.	x #11 = 3.97

Graph 7 - Calculated color differences ΔE* and subject ratings for BLUE and GREEN color samples in Phase 1A and 1B.

Also, graph 5 shows that the reflectivity of the blue sample is lower on the red region, which explains why the blue sample benefited less from spectra with high emission in red (and high CRI). Graph 8 also shows that the spectra with higher CR rendered the green color better to the observers. This can be explained because a green sample reflects other colors (including considerable amounts of yellow and red wavelengths), and consequently the appearance of this color was affected by the variations of the red to yellow ratio. It can also be seen from the charts that the results from the visual experiments were consistent with the ΔE* table. This can be explained by analyzing graph 7 which shows that spectra with high CRI were also the ones with higher green emission (green and red emission were consistent). We can only expect that higher green emission will benefit a green color sample. It is also clear from both charts that the differences between Phase 1A and 1B were negligible

5.6. CONCLUSIONS

In Phase 1 experiments examined human's sensitivity to color rendering modulation was investigated under controlled laboratory conditions. Seven LED white composite spectra of different color rendering, but equal chromaticity and light levels, were studied in terms of how they rendered a set of color samples to the human eye, in comparison with an incandescent bulb. The psychophysical experiment involved direct observation of two different double booth experimental set ups where subjects' comparisons of color palettes were solicited. The color rendering modulation performed amongst the LED spectra was primarily based on a modulation of the ratio of red to yellow emissions: yellow emissions were progressively increased to compensate as red was progressively subtracted in an effort to produce a sequence of white LED spectra of higher efficacy. Blue was held fixed and minor adjustments were made for green emission. Seven white spectra were generated and organized from highest to lowest color rendering index, CRI.

It was found that for saturated red and yellow samples, human observation was strongly associated with the rebalance of red to yellow ratio. In some cases these results were opposite to the measured values of CRI or ΔE^*. For example, color differences were much more discernible for saturated red samples under spectra of reduced red emission (and reduced CRI), which was expected and was confirmed unanimously by our subjects. On the other hand, color differences for saturated yellow samples were practically unnoticed under spectra of reduced CRI, as these spectra had higher yellow emission. This result could also have been anticipated. Visual perception of lower saturation red and yellow samples were not as predictable, and results offered noteworthy material for future steps of this investigation, as color differences were found more tolerable under mid-range CRI spectra. For example, subjects reported to be fairly comfortable with color differences observed for low saturation red samples (including red toned skin color sample) under spectra of considerably low CRI (and high ΔE^* values). Green and blue samples were considerably less affected by the color rendering modulation than the red or yellows, but it was clear that the color differences on green samples were much more discernible than the blue samples.

These results provided an encouraging baseline in regard to the relationship between the changing LED spectra and the different colors and different saturation level. It was rich information to bring to Phase 2 when these colors will be part of a full scale mock up of a realistic scenario to check if people will have similar reactions. The primary goal is to identify which reduced color renderings could potentially be acceptable to users in real life environments. The ultimate goal is to be able to assess perception of dynamic modulation of color rendering in architectural settings where the perceived color distortions may range from negligible to nil. Such a real life experimental set-up was chosen and implemented to follow these experiments because it can further substantiate the current results. It is important to bear in mind that ratings of composite white light from multi-chip LED systems rely heavily on the set of test samples used on the experiment (Schanda, 2002). The manner under which these color samples are presented will certainly have consequences in the perception and acceptance of color distortions, and consequently of color rendering modulation.

CHAPTER 6. PSYCHOPHYSICAL EXPERIMENTS - PHASE 2

6.1. INTRODUCTION

Like in Phase 1, the experiments in Phase 2 are dedicated to investigating how the visual system perceives changes in the spectral components of white illuminants, in particular, to assess human perceptual tolerances to color rendering manipulation. The principal hypothesis was that a range of color distortions caused by LED white spectra of reduced color rendering would be negligible when seen within a real life condition. The ultimate goal was to provide psychophysical evidence to support that color rendering can be "invisibly" reduced within people's periphery and thus to encourage the novel energy saving color rendering modulation control strategy. For this purpose, the visual tests were set-up to appraise the perception of changes in color rendering happening in people's periphery (stimuli placed at 10° and 20° from observers' center of gaze) in comparison with the same color changes perceived with direct observation (observers looking directly into the stimuli). In phase 2, the same control strategy studied in phase 1 was applied to a larger system, using larger LED panels and much more powerful controllers.

With the noteworthy exception of (Pracejus, 1967; Bellchambers & Godby, 1972), seldom are color perception experimental analyses conducted in the context of natural settings. In Phase 2 instead of in small booths the visual tests took place within full scale mockups of a real life scenario. Subjects looked from three different angles at two identical dining area mock-ups positioned side-by-side under incandescent (fixed lighting) and LED illumination (changing lighting with sequences of different color rendering). The psychophysical experiments were based on a "just noticeable difference" assessment but using a different approach than Phase 1. In Phase 2 observers were exposed to continuous modulation of CRI (as opposed to the discrete modulation as in phase 1). As the spectra slowly transitioned from high to low CRI subjects were asked to indicate if/when they noticed a difference in the appearance of each scene. The design of Phase 2 experiments mainly constituted the following set-up: (a) Stimuli positioned at 0°, 10° and 20° from subjects' center of gaze; (b) Stimuli consisting of a simulated real life spatial context, with prominent saturated red components; (c) LED white spectra under continuous CR modulation.

The baseline laboratory experiments from Phase 1 (Thompson & O'Reilly, 2006) confirmed two fundamental premises: (a) The color rendering modulation was mainly noticeable when looking at saturated red samples; (b) There was a reduction in sensitivity when the color changes were not seen side-by-side. In agreement with these results, previous experiments on vision physiology have found strong evidence that ability for color vision decreases in people's periphery and that this effect is deeply affected by eccentricity (Ferree & Rand, 1919; Moreland & Cruz; 1959; Weitzman & Kinney, 1969; Stabell & Stabell, 1981, 1982 and 1984); and previous evidence from vision psychology research (Simons, 2000 and 2005; O'Regan 2001; O'Regan, personal website) have proposed that people cannot detect even sizeable visual changes when these are slow progressive changes.

Phase 2 results showed that sensitivity to the color rendering modulation was strongly connected with direction of gaze (0°, 10° and 20° from stimuli), and confirmed the fundamental hypothesis, showing that the majority of subjects did not detect the color changes at 10° and 20° angles while the same distortions were noticeable during foveal[1] vision tests.

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[1] Foveal vision is the vision with the fovea. The fovea is a part of the eye, located in the center of the retina, responsible for sharp central vision, which is necessary for reading, driving, or any activity where visual detail is of primary importance. The fovea is less than 1% of the retina and sees only the central two degrees of the visual field. The Foveal vision tests performed for this research (also called 0° tests), refer to the tests performed when subjects

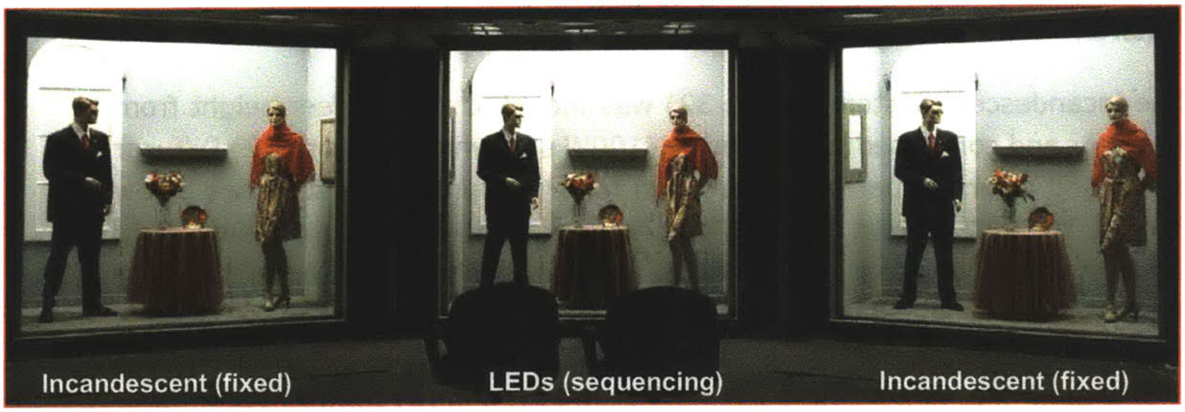

Figure 31 - Experimental set-up. Chambers #1, #2 & #3.

6.2. EXPERIMENTAL SET-UP

6.2.1. The Experimental Room

The experiment was carried out within a darkened room[2] (approximately 30 Lux) with an area of approximately 950 square ft and 11 ft ceiling height, containing three open experimental chambers of 50 square ft each, positioned on a slight angle from each other. All three chambers were decorated with the same layout and were painted with light grey matte paint to maintain neutral and smooth background illumination (figure 31). The layout and materials were selected so the setting would have a prominent saturated red component, and would work as a representative day-to-today scenario. Chamber #1 and #3 were illuminated with incandescent light and chamber #2 with three LED fixtures.

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were looking directly into the test field (chamber #2) under LED lights.

[2] The experimental room was located at LIGHT Point training Facilities at Osram Sylvania Headquarters, Danvers, MA.

6.2.2. The Lighting Systems

The incandescent system (figure 32) was mounted at nine feet height from the floor and comprised: (1) 17 bulbs (100W soft white A19) and (2) Diffuser layer, and color temperature correction filter[3] (mounted 3 feet inches below bulbs). The LED system (figure 33 A and B) was mounted at nine feet height from the floor and consisted of three fixtures, each fixture comprising: (1) An enclosure equipped with four fans and appropriate perforation for suitable heat dissipation; (2) LED panel containing the LED modules[4], a custom made digital controller and power supplies (figure 34), and (3) Diffuser layer[5].

The digital controller, mounted to the LED panel, was a custom made PCB (printed circuit board) with programmable microcontroller[6] performing PWM modulations of the four individual channels. It was controlled through a serial link from a java software interface running on a PC computer. Besides enabling full control of each color channel, the software enabled us to create any set of RYGB spectra and choose any RYGB combination individually or to sequence through multiple combinations with any time interval. The microcontroller has 128Kb of program memory and 4kb of RAM, running at a frequency of 14Mhz. The generated PWM signal has frequency of 8000Hz for a very stable, flicker-free light, and a duty cycle of 0-100% with 0.1% resolution. The PWM is amplified through MOS transistors for a total maximum output power of 250W per panel. To obtain the required stability over time, the design of the PCB took special care in reducing the dissipated heat, as well as the temperature profile.

6.2.3. The White LED Composite Spectra

The four color channels of the LED panels - controlling one single set of dominant wavelengths 633 nm (Red), 587 nm (Yellow), 525 nm (Green)

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[3] The Diffuser used on the incandescent system was an acrylic K12 prismatic lens; and the temperature correction filter was Rosco #3208: Quarter Blue.

[4] The LED panel contained 58 LED modules (6 Red, 24 Yellow, 16 Green and 12 Blue). The LED modules' specifications are: Osram Sylvania LINEARlight LED modules Red (LINEAR/633/OS/LM01A/S1), Yellow (LINEAR/587/OS/LM01A/Y2), Green (LINEAR/525/OS/LM01A/T2) and Blue (LINEAR/470/OS/LM01A/B1).

[5] The Diffuser used on the LED panel was a ROSCO #111.

[6] Specifications for the microcontroller: Atmel ATMEGA128.

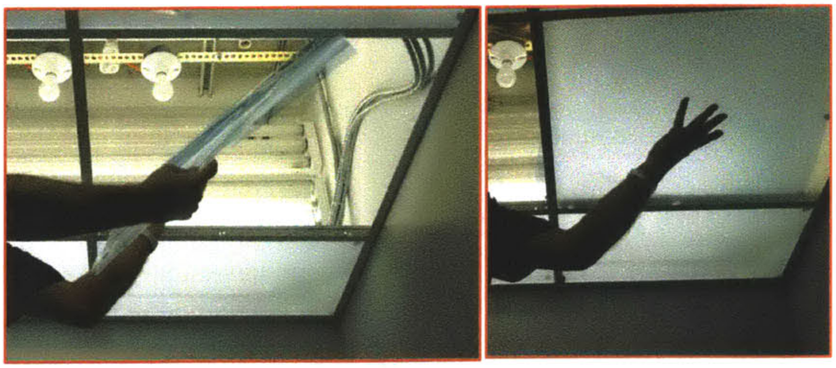

Figure 32 – The incandescent system was placed three feet above ceiling line where the diffusers and color temperature correction filters were installed.

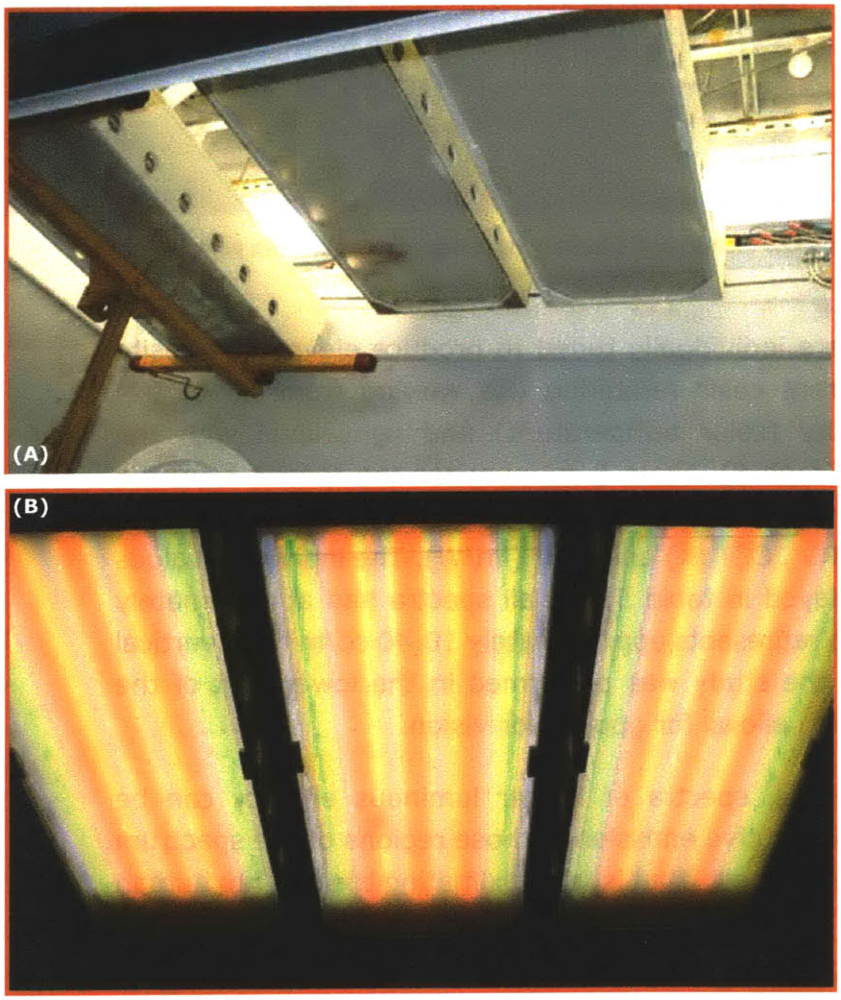

Figure 33 – (A) LED system installed and (B) operating. The system was mounted at nine feet height from the floor and consisted of three LED fixtures.

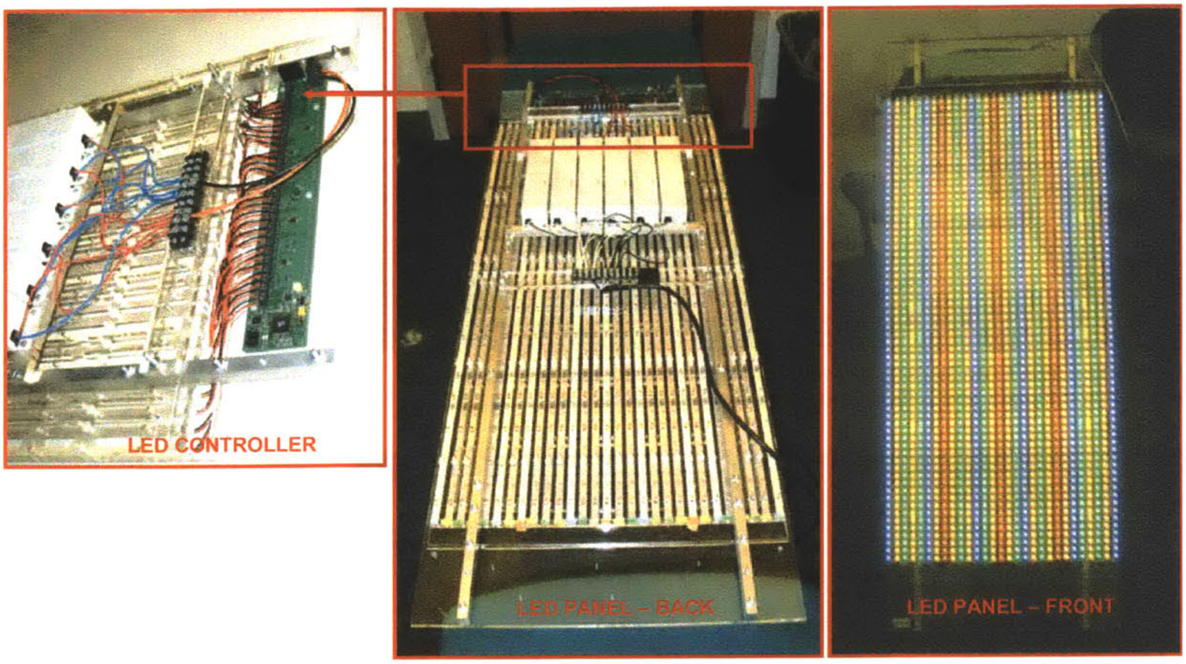

Figure 34 – LED panel containing the LED module and a custom made digital controller with power supplies.

and 470 nm (Blue) -- were individually tuned to produce eleven composite white spectra with different color rendering (Ra varying from 34 to 92) but matching chromaticity (color temperature) and light level with the incandescent chamber (Graph 8). Table 5 summarizes the results from the measurements of the eleven LED spectra and the incandescent, showing the general CRI, special CRI-R9[7], CCT (K) and LER[8] (lm/W). The individual values per light source are displayed in table 5, but all spectra had approximately 260 lux horizontally which represents approximately 10-40 cd/m^2 of vertical luminance. Therefore all the study was performed in the lower part of the photopic vision range which allows for good color vision.

As it was mentioned before, spectra of higher luminous efficacy can be obtained by increasing the relative emission in those regions of the spectrum where the eye response is greatest (that is, approximating the 555 nm human

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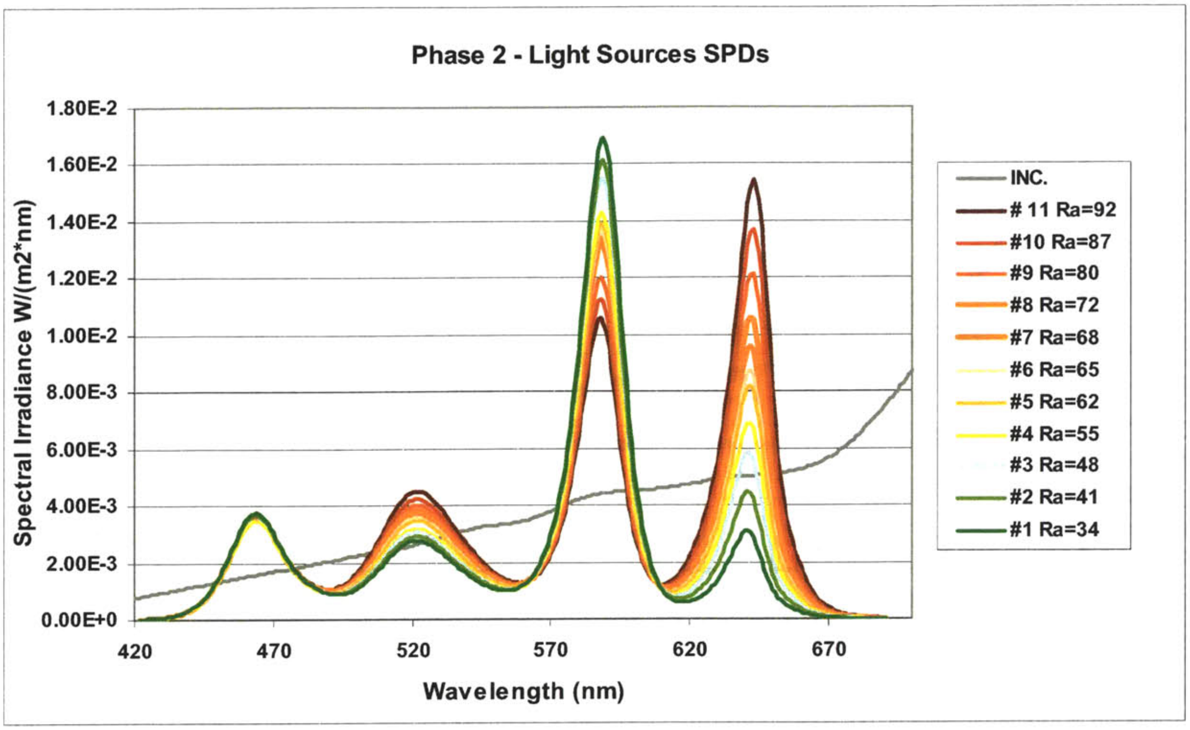
[7] In table 5, while the general CRI-Ra is as expected for incandescent lamps, it shows that the value for R9 is slightly lower than expected. This was because of the necessary color correction that needed to be done in order to adjust the incandescent correlated color temperature to that of the LED balance.

[8] LER stands for Luminous Efficacy of Radiation, which is also a way to refer to luminous efficacy, measured in lumens per Watt.

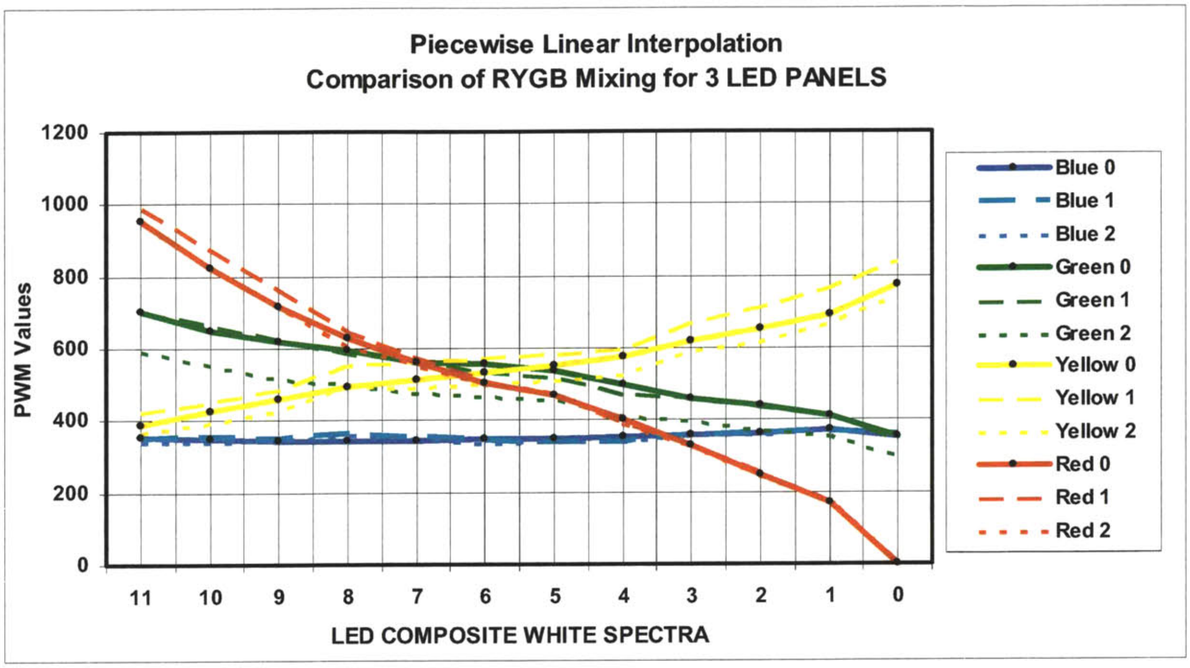


Graph 8 - Spectral power distribution, SPD, for reference and test light sources used in phase 2 experiments. The general color mixing approach used was to change the ratio of red to yellow, keep the blue component fixed and make minor adjustments to green.

	INC	11	10	9	8	7	6	5	4	3	2	1
Lux	263	264	261	261	266	262	260	259	253	262	261	264
CCT	3002	2966	2969	2970	2972	2976	2990	2981	2970	2952	2965	2975
CRI	**98**	**92**	**87**	**80**	**72**	**68**	**65**	**62**	**55**	**48**	**41**	**34**
LER (lm/W)	**273**	**312**	**323**	**334**	**347**	**354**	**362**	**366**	**374**	**386**	**398**	**410**
Watts	**n/a**	**1.00**	**0.96**	**0.93**	**0.90**	**0.88**	**0.86**	**0.85**	**0.83**	**0.81**	**0.78**	**0.76**
x	0.4376	0.4377	0.4375	0.4378	0.4376	0.4377	0.4375	0.4380	0.4377	0.4385	0.4378	0.4370
y	0.4058	0.4015	0.4014	0.4022	0.4020	0.4027	0.4041	0.4040	0.4020	0.4013	0.4016	0.4012
u-v	0.0010	0.0011	0.0011	0.0009	0.0009	0.0006	0.0001	0.0002	0.0009	0.0013	0.0011	0.0012
R9	**84**	**94**	**69**	**31**	**-15**	**-37**	**-59**	**-74**	**-109**	**-151**	**-194**	**-242**

Table 5 – Summarized results for LED spectra and incandescent used in experiments.

sensitivity spectral peak, explained on chapter 2). The general color mixing approach used in phase 2 was the same described in chapter 5 for the phase 1 experiment which is to change the ratio of red emission to yellow emission, keep the blue component fixed, and make minor adjustments to green. The main objective of this particular approach was to compensate for the reduced red emission with yellow emission to attain higher efficacy sources at the



Graph 9 – Color mixing strategy of eleven LED white spectra illustrated in terms of PWM values. It is clear how spectrum #1 has a drastically reduced amount of red energy and proportionally increased amount of yellow energy in comparison with spectrum #11. Blue and green energies are stable through the eleven mixtures.

same color temperature. All the balance against the blue and green spectral components is obtained with yellow emission, red emission is increasingly reduced (graph 9). Consequently, spectrum #1 (lowest in red energy, highest in yellow energy) presents very poor rendering, but high efficacy.

The information listed in table 5 reflects the results from the final measurements which refer to a sum of the three LED panels. The measurements were performed inside of the experimental chambers (chambers #1 and #3 for the incandescent data, and chamber #2 for the LED data) with the complete experimental set-up prior to the tests. During each measuring section a calibrated photodiode (the port of the integrating sphere input to a spectroradiometer) was placed on top of the table located at the center of the chamber, six feet beneath the ceiling line, and the spectral power distribution, SPD, of the light was measured[9] (figure 35). From the SPD the information listed in table 5 was calculated. Prior to these final measurements, using

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[9] All measurements were conducted at Osram-Sylvania Lighting Research Center facilities (Berverly, MA) by Dr. Robert Levin and Joseph Laski. Measuring instrument used was an Ocean Optics, Inc. Model USB2000 spectroradiometer with operation and data reduction by OSRAM SYLVANIA proprietary software.

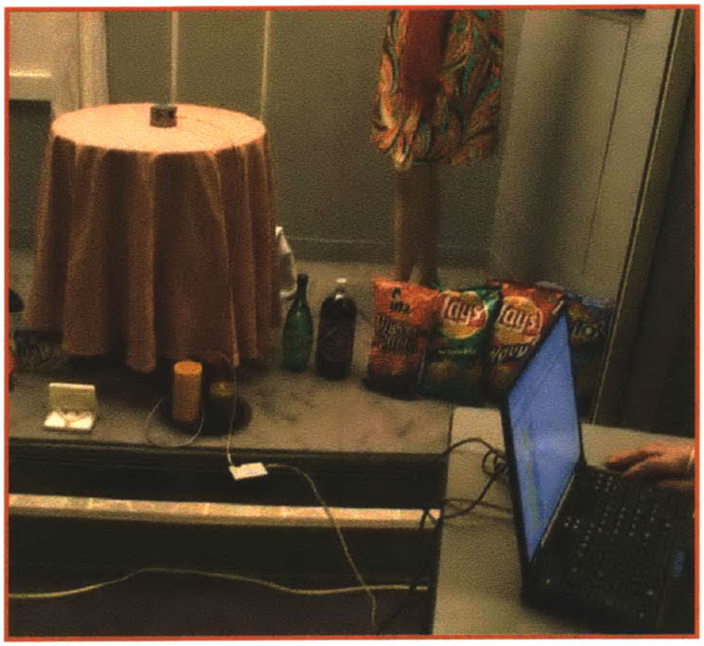


Figure 35 – Procedure to measure the light spectra from incandescent and LED lighting systems were conducted at Osram-Sylvania Lighting Research Center and used an spectroradiometer with operation and data reduction by OSRAM SYLVANIA proprietary software.

the same equipment and technique, each LED panel had been calibrated individually in the laboratory.

During the calibration procedure, the CRI modulation control technique was implemented to generate the desired spectra to be used in the psychophysical experiments. In order to create the eleven composite white spectra of various CRI and fixed CCT and lumen output, an exhaustive trial-and-error procedure was used, whereby the input of each color emission RYGB was adjusted (through the laptop computer directly into the LED panels) depending on the results from the measurements. This was necessary in order to match the chromaticity of the LED spectra used in Phase 1, and to account for the added effect of the much larger space of the chambers in Phase 2. For example, spectrum #11 (92 CRI) was spectrally tuned, preserving CCT and lumen output, to obtain spectrum #8 (72 CRI) using only 90% of initial wattage. Additional gains were achieved by adjusting spectrum #8 to obtain spectrum #5 (62 CRI) using approximately 85% initial wattage or even adjusting spectrum #8 again to obtain spectrum #1 (34 CRI) this time using 76% initial wattage. Table 5 illustrates that rebalancing from high CRI (spectrum #11) to

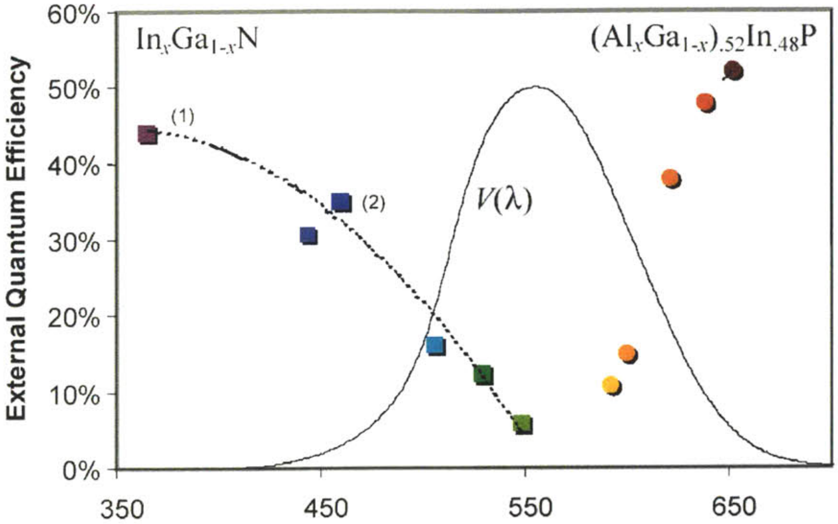
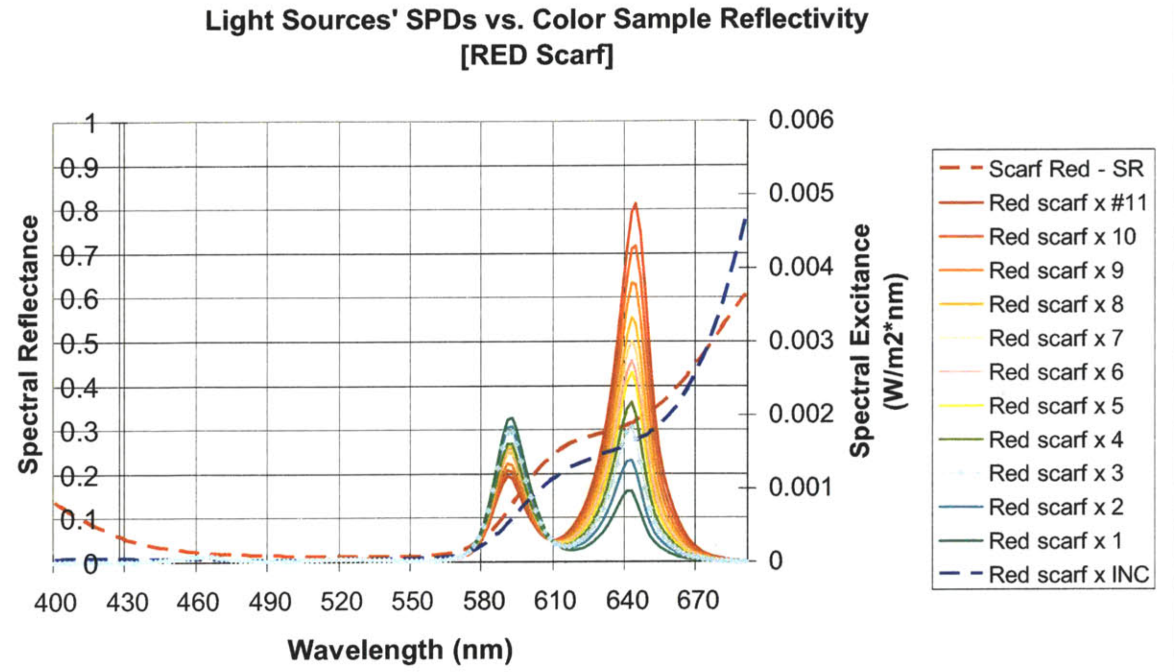


Figure 36 - External quantum efficiency of high-power (>1 Watt input) LEDs, with V (λ)curve. (1) Nichia Chemical Co.; (2) Cree; Other data from Philips Lumileds Lighting company. Data and picture from Philips Lumileds Lighting Company, by Nathan Gardner.

low CRI (spectrum #1) reduced the wattage to as much as 76% of the initial wattage with the same lumen output.

It is very important to point out that the values of luminous efficacy of radiation, LER (lm/W) were calculated with an assumption of equal 100% power efficiency for all colors. While this will be rather challenging to achieve on a commercial level, the viability of a technique for obtaining a favorable tradeoff between CRI and efficacy rests on the relative efficacy of each of the colors used. The energy savings illustrated in table 5 are valid for a situation of all LED colors being of equal power efficiency (not necessarily 100%). However, this is not yet achieved by semiconductor technology today (LED Magazine, 2004; Schubert, 2006). Most notably, the presented control technique of modulating color rendering to increase efficacy depends on a technological breakthrough for higher efficiencies of yellow LEDs to succeed. Currently, the efficiencies of each color are still very different from each



Graph 10- Spectral reflectance of red scarf (red dashed line) against spectral power distribution, SPD, of the eleven product spectra (solid colored lines for LEDs, and dasehd blue line for incandescent product spectra).

other[10] [Blue=25% (20 LPW[11]), Green=20% (110 LPW), Yellow=9% (44 LPW), Red=15% (38 LPW)] the yellow LED clearly being the least efficient of all colors. The efficiencies of these devices are directly related to the technology of each type of semiconductor material (InGaN compound semi-conductor for Blue and Green; and AlInGaP for Yellow and Red). Figure 36 shows the trends for power conversion of the various colors (Zukauskas, Shur & Gaska, 2002; Schubert, 2006; Narukawa et al, 2006).

6.2.4. Product Spectra

Graph 10 shows the spectral reflectance of the red scarf along with plots of

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[10] Typical state-of-the-art values for electric-to-light efficiency from the literature, industrial press releases, and commercial vendor datasheets. Example can be found at Osram Sylvania's on line catalogue at: http://catalog.osram-os.com/media/_en/Graphics/00040302_0.pdf and http://catalog.osram-os.com/media/_en/Graphics/00038996_0.pdf

[11] LPW stands for "Lumens per Watt", which is the same as lm/W.

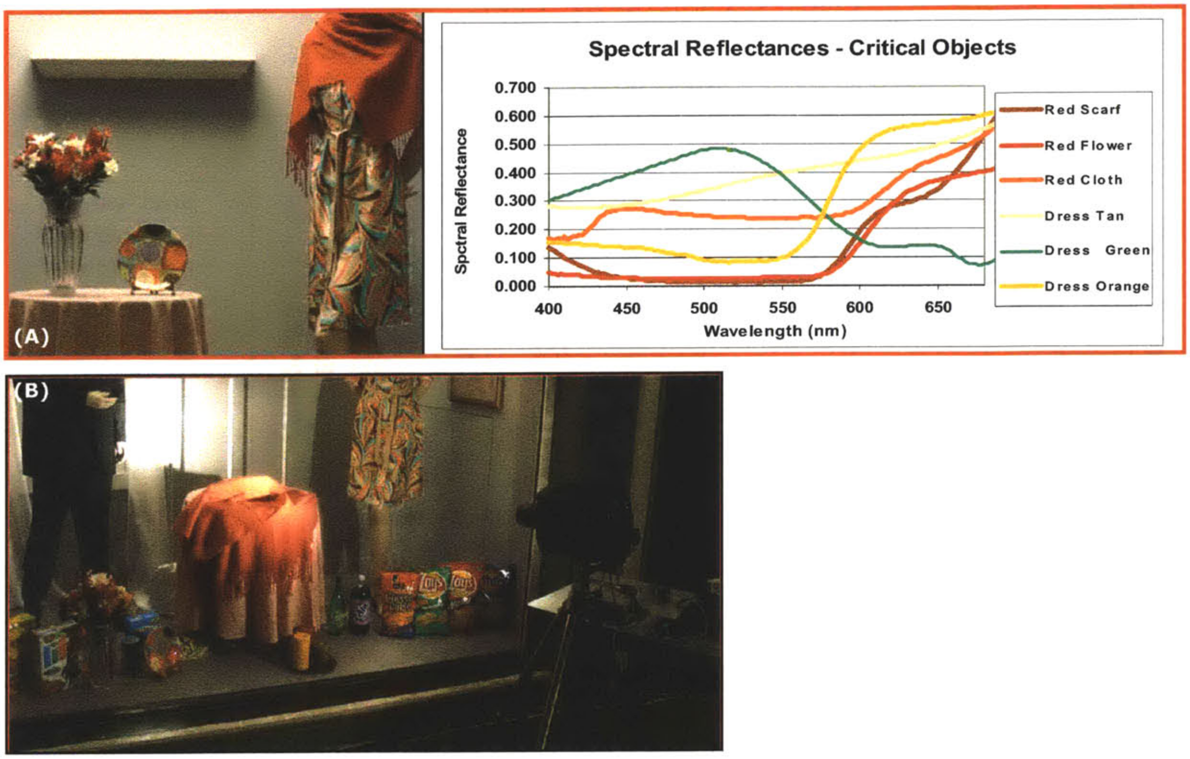

Figure 37 - (A) Spectral reflectance curves of the most critical objects used during the experiments. (B)The spectral radiance measuring procedure. The reflectance spectra were obtained by comparing the measured spectral radiance to that obtained from a barium sulfate plaque placed at the location of the color samples. The spectral reflectance measuring instrument used was a tele-spectroradiometer.

eleven "product spectra". The product spectra were generated by multiplying the scarf's spectral reflectance by the eleven SPDs of the light sources used in the experiment and represent the color balance reflected from the red material to the subjects' eyes under each illuminant during the experiment. In the graph 10, they are represented by the solid colored lines. Measurements of the scarf's reflectance and of other materials located in the experimental chambers (such as the mannequin' dress, table cloth and flowers) were performed within chamber #1 after final layout was finalized[12] (figure 37). The red dashed line in graph 11 represents the spectral reflectance for the red scarf, the most critical object for the purposes of this investigation (figure 31).

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[12] The spectral reflectance measuring instrument used was a Photo Research, Inc. PR-705 Spectra Scan tele-spectroradiometer. The reflectance spectra were obtained by comparing the measured spectral radiance to that obtained from a barium sulfate plaque placed at the location of the color samples.

The plots show how the individual colored emission from the LED spectra interacted with the reflectivity of the red scarf. For example, LED spectra #11, represented by a red solid line (highest in red emission and highest CRI), has always the highest energy in the red region and the lowest energy in the yellow region. Although all eleven spectra are relevant for this investigation, the focus of this analysis should be on the medium CRI spectra #4, #5, #6 & #7. This is because the high CRI spectra such as #9 and #10 will most certainly provide acceptable rendering for the observers, and very low CRI spectra such as #2, and #1 should generally provide poor rendering. Therefore there is a particular concern with the results for the med range spectra to check how the reduced CRI influenced the visual appearance of the chambers.

A critical part of this analysis is to carefully examine the relationship between the spectral characteristics of the illuminants and the reflectivity of the objects, shown in graph 10. From the plot it is clear that the scarf will reflect almost no blue or green light. That it will be almost entirely dependent on the amount of red emission from the white LED spectrum. Looking at the reflectivity curves from the other colors used as part of the test scene (beige, orange, light-green, etc) it is clear that these colors will depend much less on the red emission from light sources, because are less saturated (even the other red colors).

6.3. PROCEDURE OF PSYCHOPHYSICAL EXPERIMENT

Thirty subjects (eleven male and nineteen female) with normal color vision participated in the experiment. The main goal of the experiments was to determine if and when the subjects would detect incremental changes in the color rendering of eleven LED white spectra when chromaticity and illuminance stayed the same as the incandescent reference. The experiment was divided in three sections, each dedicated to threshold detection in peripheral (20°), off-center (10°), or foveal vision (0°) (figure 38). For all three sections the main procedure stayed the same: subjects sitting in a central position facing the chambers.

In chamber #2, the LED panels were set to a continuous sequence of the eleven LED white spectra of different CRI (figure 39), and in the incandescent

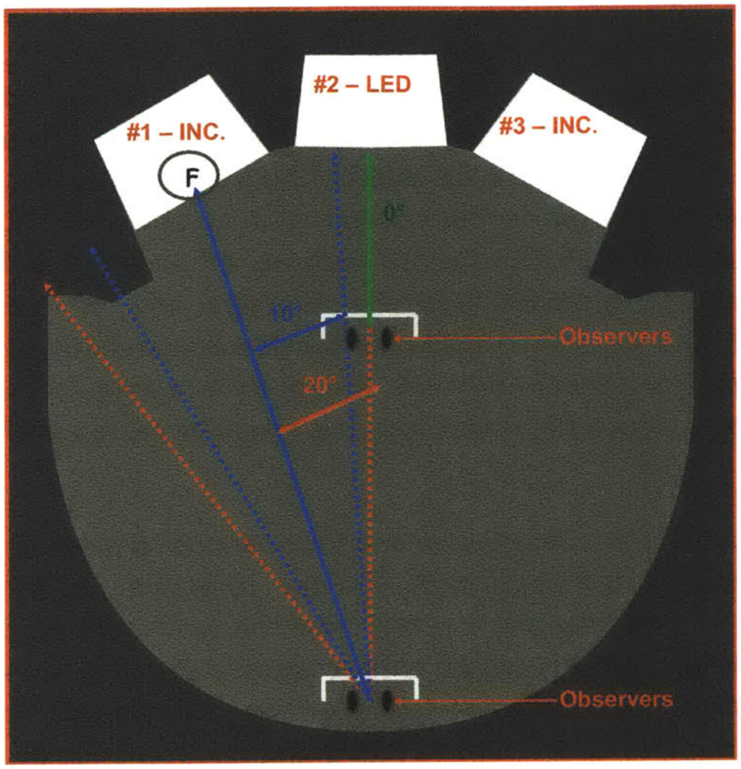

Figure 38 – Floor plan of experimental room showing the viewing positions of 20° (Red dotted line), 10° (Blue dotted line) and 0° (Green dotted line) in reference to the different visual tests performed.

chamber the lighting condition remained unchanged. The subjects (two at a time) were instructed to focus and keep their gaze fixed at the flower arrangement located at the center of the incandescent chamber, while the LED chamber was prompted to sequence through the eleven spectra for thirty seconds. At the end of these thirty seconds, the subjects were instructed to answer a questionnaire, by marking (yes or no) if they noticed any change in the appearance of either chamber, and (if they did) when was it that they first detected the change (in the beginning, middle or end) of the experimental section.

The change in the spectrum composition of the LED white light was done gradually and continuously in two different modes: from highest to lowest CRI (sequence going from spectrum #11 to spectrum #1) and vice-versa, from lowest to highest CRI. Other than these two sequences a control test was introduced, which consisted of a "dummy run" (same experimental procedure but with no sequencing and therefore no color rendering change) to test

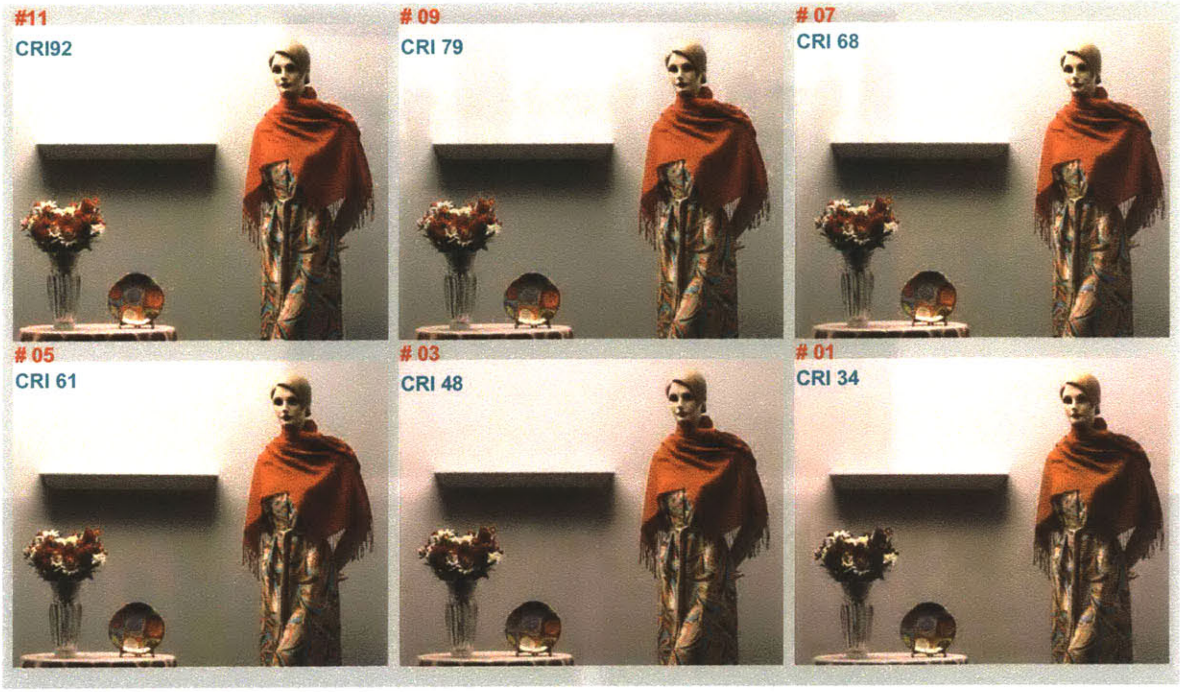

Figure 39 – Summarized sequence performed by LED system in chamber #2. The color in this picture reproduction is only approximate due to limitations of the photographic and printing processes. The LED panels were set to run a continuous sequence of the eleven LED white spectra of different CRI but same CCT and light levels, while the incandescent chamber remained unchanged. The sequence shows that the color rendering was gradually reduced from CRI 92 (spectrum #11) to CRI 34 (spectrum #1).

the validity of the judgments made by the observers. By making the rate of change between spectra during the sequence sufficiently slow the observer's state of adaptation followed the change closely enough and they had no consciousness of the kinetics of the system. From a series of pilot experiments, it was found that a rate of change such that the entire sequence of eleven spectra took sixty seconds was suitable, considering that the intention was to test the worse case scenario. The experimental procedure was repeated in a certain order unknown to the observer.

The 20° experimental section was divided in six intervals: two intervals for decreasing CRI sequence; two intervals for increasing CRI sequence; and two intervals for control test. Subjects sat 30 feet away from the chambers. The 20° angle was measured between the subjects' direction of focus (flowers in chamber #1) and a reference point (flowers in chamber #2). Only two chambers were compared at a time, so that LED chamber #2 was presented side-by-side with one of the incandescent chambers (either chamber #1 or

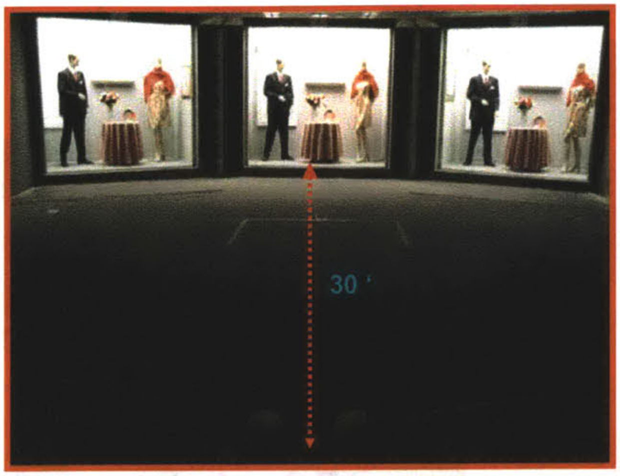

Figure 40 – Experimental setting for 20° psychophysical experiments. Subjects were instructed to keep their gaze fixed at the flower arrangement in the incandescent chamber, while the LED chamber (at 20° and peripheral vision of observers) was prompted to sequence through the eleven spectra of different CRI for thirty seconds.

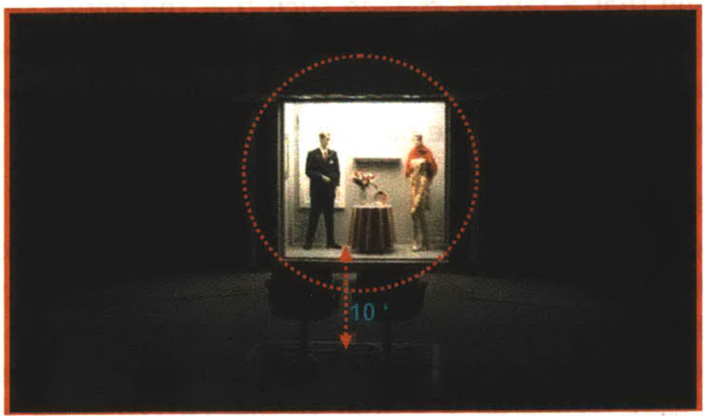

Figure 42 – Experimental setting for Foveal vision (0°) psychophysical experiments.

#3) (figure 40). This was done in order to avoid biases judgments toward the subjects' left or right side.

The 10° section was very similar to the 20° section with the same positioning and instructions for subjects. The difference was that for the 10° section the layout was modified to allow a 10° angle of vision between subjects' direction of focus and the reference point (figure 41). The foveal vision (0°) section was divided into four intervals: two intervals for decreasing CRI sequence; one interval for increasing CRI sequence; and 1 interval for the control test.

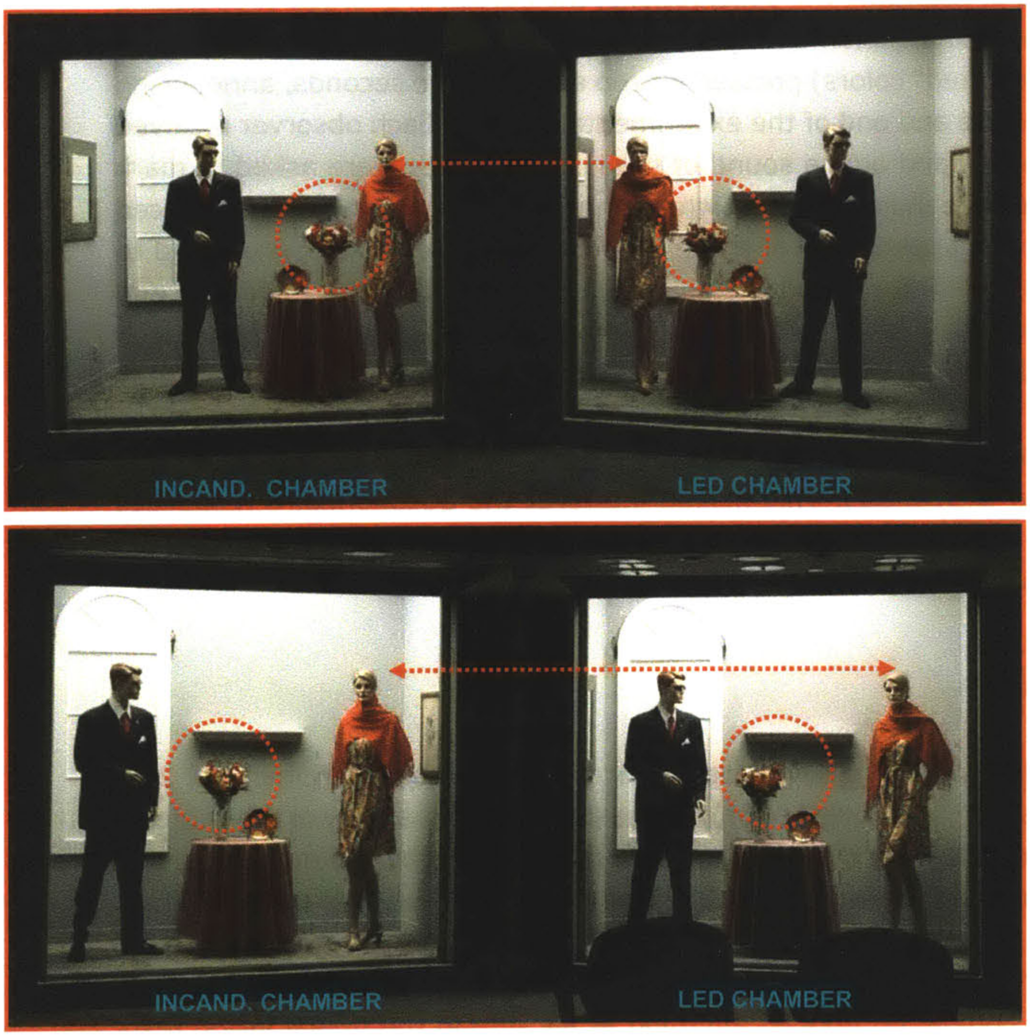

Figure 41 – Experimental setting for 10° psychophysical experiments. The layout was modified to allow a 10° angle of vision between subjects' focal point (flowers in inc. chamber) and the reference point (flowers in LED chamber).

Subjects sat 10 feet away from chamber #2, and were asked to look freely within chamber #2, while the LED lighting was sequencing (figure 42). The viewing distance (ten feet for foveal tests and thirty feet for 10° and 20° tests) was determined by the desired angle of separation between the boundaries of the illuminated field (one chamber for the foveal tests and two chambers for peripheral vision tests). It was necessary to fill a significant part of the visual field in order to provide adaptation to light levels, and therefore the distance could not be too large with respect to the whole illuminated test field, or its angular size would have been too small.

As a method of recording the observations, the person in charged of operating the experiment and implementing the changes from high CRI ("ideal" colors) to low CRI ("distorted" colors) pressed a beep every twelve seconds, announcing the start, middle and end of the experimental section. Each observer received a questionnaire, and at the sound of the last beep they were asked to mark the questionnaire indicating if or when (in which beep interval) they noticed a change in the appearance of either chamber. Precisely, they were asked to mark when they first noticed the change; if in the beginning, middle or end of the interval. The beep cycle assisted the subjects with the timing of each interval and allowed them to locate when they first notice a change (if they did). The 11 spectra were classified in three color rendering regions: High CRI (spectra #11, 10, 9 & 8), Medium CRI (spectra # 7, 6, 5 & 4) or Low CRI (spectra # 3, 2 &1). This helped interpret the questionnaire responses (beginning, middle or end) and determine if they noticed the change at a high, medium or low CR range.

6.4. RESULTS

Graph 11 shows the combined results for the three tests (Peripheral at 20°, Off-Center at 10° and Foveal at 0°), revealing that the majority of the subjects did not appreciably notice the changes in color caused by the modulations in color rendering. However graph 12 shows that this result was not consistent throughout all tests, as subjects' responses were notably different for the 0°, 10° and 20° assessments. While in the 20° peripheral vision tests less than 10% of the population noticed anything at all, during the foveal vision tests the majority of the population reported to have noticed something changing in the scene. The result from the control test confirmed the validity of the judgments made by the observers, and shows that some changes were reported when none had, in fact, occurred, but these were sufficiently seldom $(p<0.1)$[13] to validate the conclusions drawn from the tests.

The results on graph 12 demonstrate that sensitivity to color rendering modulation was strongly connected with direction of gaze (20°, 10° and 0°), with significant $(p<0.1)$ reduction in sensitivity as the test field moved away from the foveal field of view. They confirmed the fundamental hypothesis, showing that most subjects did not detect color changes in their periphery (20°), while they did perceive these changes with direct observation (0°). Moreover, the results provide noteworthy information concerning visual perception at 10°. As the proportion of people noticing change at 20° did not reach significance, it is clear that subjects had no discernment concerning the color changes at this angle, and therefore we will focus the following analysis on a comparison between the results from the 0° and 10° vision tests.

The 10° tests represented perhaps the most provocative stage in this investigation, as we did not have sound expectations for their outcome, and the 10° angle has been vastly studied in terms of color perception (Lozano & Palmer, 1968; Morren, 1979; Katori & Fuwa, 1979; CIE, 1963). The 10° angle represented in this study the exact middle position between the peripheral view point (20°) and center of gaze, and the results revealed that this angle also represents a central interval for color perception. Graph 12 illustrates a sequential ascendance in sensitivity from peripheral to foveal verifying that 10° represented a middle point in terms of sensitivity to the color rendering changes. But even though there was a significant increase in sensitivity at this point in comparison with the 20° position, still less than about 50% of the subjects noticed any CR change. This shows that at 10° angle subjects had limited sensitivity to the changes in color and/or brightness, and substantiates that color rendering modulation can be made unnoticeable even closely to foveal region. On the other hand, the number of people noticing the changes indicates that further research should be encouraged to examine in more detail the various aspects of visual performance correlates for this particular field of view (such as rates of changes for LED spectra, light levels, color

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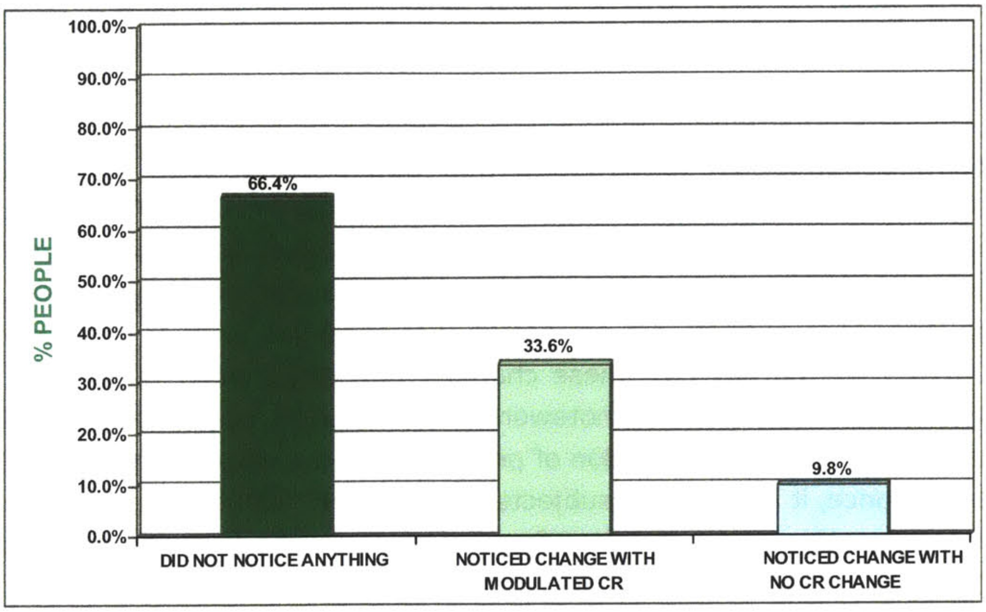
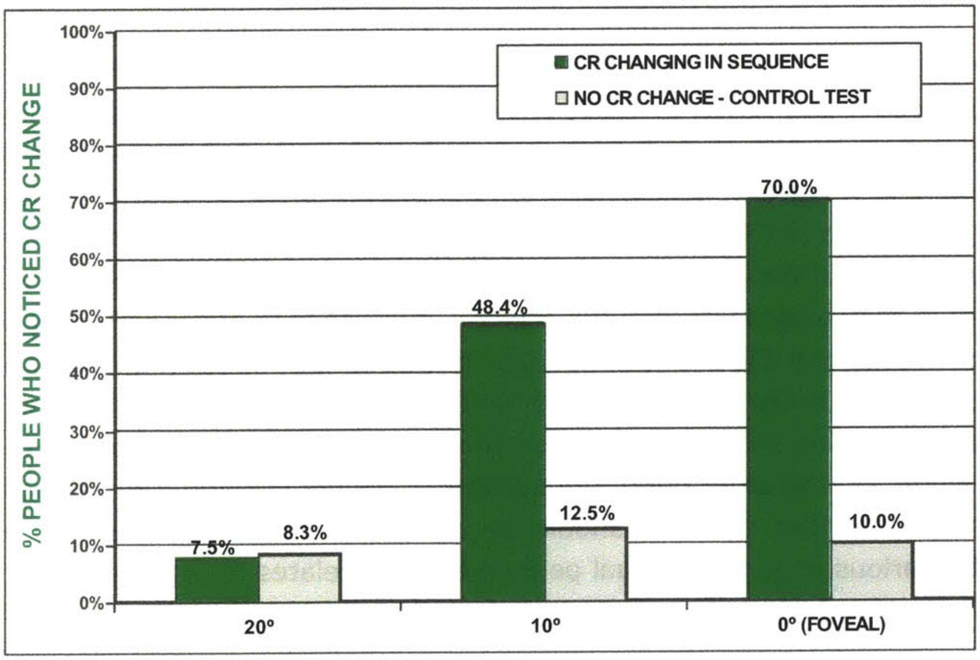
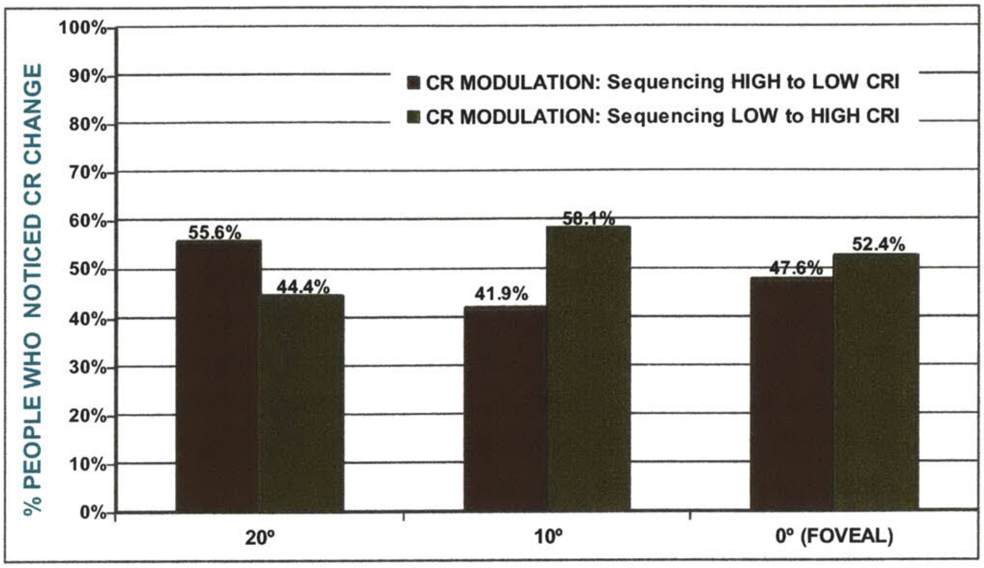
[13] Statistical analysis were performed to test the significance of the results from each visual test. Two statistical tests types were used: (1) proportion z-test, unequal variance, and (2) one proportion z-test. Information retrieved from: http://en.wikipedia.org/wiki/Statistical_hypothesis_testing



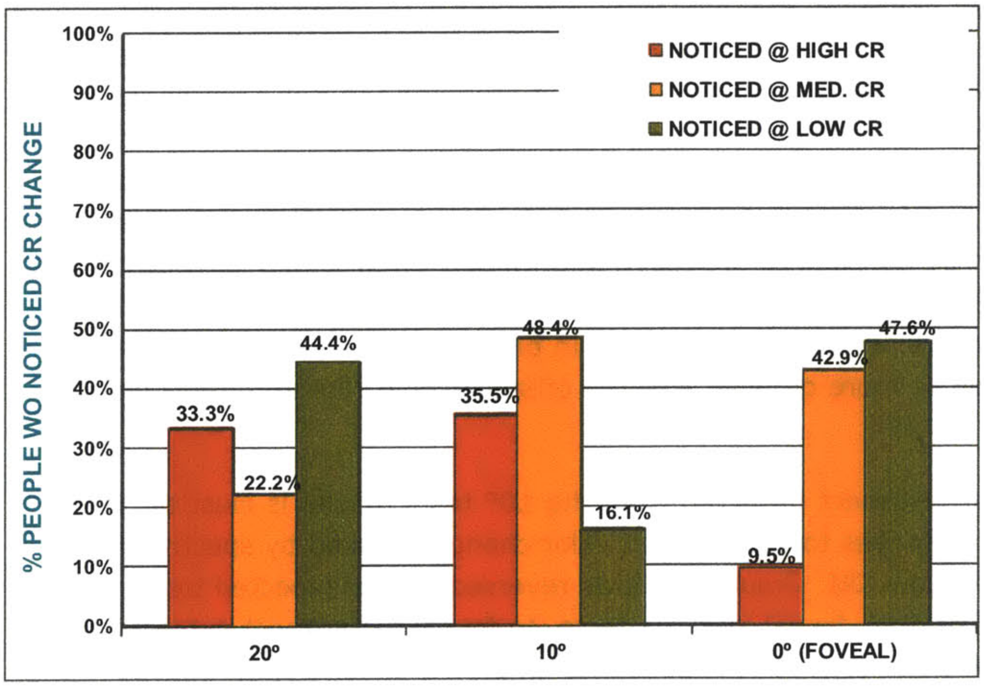
Graph 11 – Combined results for 20°, 10° and 0° tests.



Graph 12 – Results for 20°, 10° and 0° tests and control tests.



Graph 13 - Results for 20°, 10° and 0° tests for different sequence modes.



Graph 14 - Results for 20°, 10° and 0° tests for different Color Rendering Index.

temperature, distance, colors within the room other than red, etc.) in order to achieve an effective (and truly invisible) control strategy.

Graph 13 shows that in both foveal and 10° tests there was no significant ($p>0.5$) perceptual difference between the two sequence modes (*increasing* or *decreasing* CR). In practical terms, this is indicating that color rendering modulation could be made unnoticeable during both types of transitions, that is: (a) when people move closer to a target area and system would be prompt to increase CR; or (b) when people move away from a target area and system would decrease CR. In practical terms, that demonstrates that no restriction would apply for either of the two studied sequencing modes, which is encouraging for future research and future implementation.

Something worth of note were unsolicited comments from a group of the observers who, during the 10° tests, spontaneously reported to have noticed the lights "dimming up" (when CR was increasing), or "dimming down" (when it was decreasing). These comments suggest that, at 10° view angle, the change in CRI (by adding or subtracting red energy from the LED mixing) may have made lightness changes more perceptible to subjects than the actual changes in the chromatic aspects of colors (hue and saturation). The observers seem to have noticed a change in *brightness* and not necessarily a *color* difference. The formal research questionnaire did not ask *what* the observers noticed, but only *if* they noticed any change in the scene and *when* it happened. Therefore these informal reports cannot be taken as results per se, but can be considered attractive information when joined with past findings from fluorescent research. Further research should be encouraged that would evaluate perception of changes in brightness and chromaticity in isolation, as well as more detailed analysis of sequencing rate and direction of change.

Another qualitative aspect observed from the 10° tests results is illustrated from subjects' responses to the different color changes evoked by spectra of High, Middle and Low CRI. Graph 14 shows reversed and unexpected trends comparing results from foveal and 10° tests. In foveal tests, most subjects only noticed the changes when the sequence employed spectra with reduced CRI (Ra 68 to 34) which is when greater color distortions happen, and was foreseeable. But in the 10° tests most subjects noticed changes when looking at the mid to high CRI range (Ra as high as 94), which was unpredicted. It was expected that at 10° subjects would notice the most prominent color distortions (caused by spectra of low range CRI) and that the color changes promoted by spectra of higher range CRI would only be noticed with foveal observation. Results show that the opposite happened. It can be inferred that during foveal tests, when people were looking directly into the scene, they were attentive to all details within the chamber, and only detected the more outstanding color distortions. But when looking at the same scene from 10° angle, they saw the collective average of what was happening, and then captured the smaller color changes caused by spectra of higher CRI. Further research could evaluate perception of CR changes resulting from sequencing spectra in high, middle and low CRI ranges in isolation.

6.5. CONCLUSION

The experiments tested an initial strong hypothesis that people would not notice a certain class of color distortions when these happened (a) immersed within a 'real life' spatial context, (b) in people's periphery at 20°; and (c) under continuous modulation. Ultimately it was predicted that modulations of color rendering would be invisible at people's surrounding areas. To support such a hypothesis previous psychophysical evidence strongly indicated that color vision decreases with eccentricity (Ferree & Rand, 1919; Moreland & Cruz; 1959; Weitzman & Kinney, 1969; Stabell & Stabell, 1981, 1982 and 1984), and that people cannot detect even sizeable visual changes when these are slow progressive changes (Simons, 2000 and 2005; O'Regan 2001; O'Regan, personal website). These previous evidence can be joined with the results from Phase 1 baseline experiments (Thompson & O'Reilly, 2006), which indicate reduction in sensitivity when color changes were not seen side-by-side. Phase 1 baseline study also provided confirmation that saturated red components represented the worse case scenario for perceiving the CR modulation in a discrete sequence. These propositions were the foundation of the design of Phase 2 experiments.

Results from Phase 2 provide strong indication that continuous modulation of CR within a 'real life' spatial context can be made invisible at people's surroundings. The results first confirmed the initial fundamental hypothesis, showing that the vast majority of subjects had no discernment of any color changes at 20° angle tests, while during foveal tests the same color changes were noticeable for most subjects ($p<0.1$). Secondly, the results for 10° angle reiterated that sensitivity to the CR modulation was strongly connected with direction of gaze, when they demonstrate a sequential ascendance in sensitivity from 20°, through 10° to 0° fields of view. However, it is important to point out that even though there was a significant increase in sensitivity to color changes from 20° to 10° fields ($p <0.1$), still less than about 50% of the population noticed any change during the 10° tests. This shows that at this angle subjects still had limited sensitivity to the changes in color and/or brightness and substantiates that color rendering modulation can potentially be made unnoticeable even closely to foveal region.

Phase 2 results also provided qualitative information about perception of color changes at the three tested fields. While no perceptual difference were found to the two LED sequencing modes (spectra sequencing to gradually decreased or increased CRI); Persuasive perceptual differences were found to different color changes evoked by spectra of High, Middle and Low CRI; as reversed and unexpected trends were found comparing results from foveal and 10° tests.

As much as these qualitative findings (highlighted by the results from the 10° tests) were truly provoking, it is important not to over-interpreting their significance in the light of potential limitations of the experimental procedures for inspecting such specific aspects. In order to have confirmatory results concerning, for instance, differentiated visual sensitivity to changes in lightness and chromaticity within a room, it is necessary to investigate these two aspects in isolation. But psychophysical investigations of color perception in the presence of context should be encouraged when progressing into such a specialized research path. For future implementations of highly controlled LED system, it is important that even the most rich color perception psychophysical evidence from laboratory results be put to test. The world around us is way messier than the laboratory conditions, and it is important for practitioners to receive convincing demonstration that results from pristine laboratory experiments can be extrapolated to real life.

CHAPTER 7. CONCLUSION

The lighting community in the academic, corporate and governmental spheres firmly believes that LED Illumination has the potential to revolutionize the lighting market, and expects that in the next few decades, general illumination design and technology will undergo a remarkable transformation. In comparison with conventional lighting, LEDs are more efficient, have a longer life of operation, are rugged and compact, produce the entire color spectrum, and are fully controllable (Zukauskas, Shur & Gaska, 2002). Traditionally, LEDs have been used as indicator lights, replacing small incandescent lamps and have only recently become widespread in niche applications such as signage, backlighting, mobile devices, traffic signals, and large area displays. Today high brightness (HB) LEDs (> 1Watt) are being used in an ever expanding variety of lighting applications. However, the real challenge is to improve product performance and overcome technical barriers so that LEDs will move into general lighting displacing traditional light sources such as incandescent and fluorescent bulbs. The energy that would be saved is estimated to be six to seven percent of total national energy usage. Twenty-two percent of the nation's electrical power is consumed by lighting (Navigant Consulting, Inc, 2006).

This thesis was inspired by a provocative architectural lighting idea: bring the (multi-chip LED-based) lighting of unoccupied spaces to minimum color rendering to reduce energy consumption without altering the appearance of the lights or reducing light levels. This idea is based on two principles: (1) while modulating color rendering, the light level and color temperature can stay constant and hence the appearance of the modified white light can stay the same; (2) There is a strong trade-off between color rendering and luminous efficacy. That is, lower CR results in more lumens per watt. While dimming lights is well understood as an effective method to save energy in unoccupied spaces, it has also been shown that dimming can be unacceptable for open-public spaces because darker areas appear uninviting or potentially unsafe. Because light levels and color temperatures can be held constant while reducing CR, such an energy savings control mode could potentially be unnoticeable to people approaching an area under reduced CR or looking at it from afar. The ability to lower CR in marginally occupied spaces that would not tolerate dimming could potentially tackle a long standing energy savings challenge: lighting energy wasted in public spaces where large empty areas often need to remain *on* at full power during expensive peak hours. Such a technique if successful could allow peak time wattage decreases. For example, suppose that someone is walking toward an unoccupied area illuminated with low CR, and the lights gradually shift to superior color rendering, so that when the person actually arrives in the area it is lit with high CR. Such strategy could save up to 23% of energy (table 6). Another circumstance that could make use of the reducing CR technique can be found in spaces using daylight. Artificial lighting used in day-lit spaces must stay *on* at full power the entire business day. If the appropriate color rendition is provided by the daylight component, artificial LED lighting could be tuned to lowest color rendering/ highest efficiency mode with no loss in visual quality.

It is notable that while modulating color rendering, the light level and color temperature can stay constant and hence the appearance of the modified white light stays unchanged. But how colored surfaces and spaces are perceived under a light with changing color rendering is a key question. The research work presented in this thesis is based on three incremental psychophysical experiments investigating the perception of color under modulated color rendering in people's periphery (10° and 20° away from center of gaze), to test the hypothesis that a range of such generated color distortions would be negligible in the context of real life settings. The ultimate intent was to provide psychophysical evidence to support that color rendering can be manipulated "invisibly" in people's surroundings and thus to encourage the above described energy savings control strategy. If this hypothesis is proved, the unique attributes of LED lighting clearly suggest a pathway to harvest the energy conservation potential associated with occupancy sensing and daylight harvesting.

Three main experimental conditions were tested: (a) Observers looked straight at the test field (a full scale mockup simulating a dining area) illuminated with eleven LED spectra in a continuous sequence of different color renderings. Two sequencing modes were tested: LED spectra sequencing from high to low CR and vice-versa; (b) The illuminated test field was placed at 10° or (c) 20° away from observers center of gaze. Results confirmed the fundamental hypothesis showing that the vast majority of subjects did not notice color changing in their periphery (20° away from center of gaze) while the same color changes were very noticeable with direct observation. In all three tests, there was no significant difference between the two control sequences which gradually *increased* or *decreased* CR. This demonstrates that no restrictions would apply for either of the two studied sequencing modes. The results also showed that people were much more sensitive to color changes happening closer to their center of gaze (10° away). But even within this much more color-sensitive field, the perception of CR changes was still rather limited. According to the majority of subjects the lowest noticeable CR in the 10° field of view was 72. This indicates that although it would be more difficult to reduce CR within 10° visual fields, it may be possible.

The experiments confirmed to a quantified extent the hypothesis that it could be feasible to implement reduced CR modes in unoccupied or partially occupied spaces. The results strongly suggest that, from the visual perception point of view, this control strategy is viable. The conclusion is that the proposed CR modulation control technique may be appropriate for unoccupied areas, as opposed to partially occupied areas. This is because when considering partially occupied spaces, occupants could be looking anywhere, and therefore it is hard to assume that the area under changing CR will be kept within the observers' peripheral vision. These results challenge a current assumption that one single optimized color rendering should be the only thing to look for. This work suggests that different color rendering qualities may be desirable and achievable within one single environment, either to enhance appearance of objects or to maximize energy savings. Further psychophysical testing can be performed to provide a gateway to develop a commercial system.

Because the experimental set-up was purposely designed to compose a worse case scenario, it is reasonable to extrapolate some of the conclusions. For example, the rate of change in the control sequencing (from high to low CR and vice-versa), was 60 seconds for one entire run (one sequence through all 11 spectra), which can be considered an extremely fast rate, compared to the 3 to 6 minutes rates used in previous experiments (Crawford, 1959; Crawford & Palmer, 1961). Therefore we can infer that a slower rate could make the CR changes even more tolerable. Another speculation could be made in regards to colors in the space, knowing that visual perception of CR is strongly dependent on the range of colors within the illuminated scene. The test scene was intentionally designed to contain prominent saturated red components, knowing (from the baseline experiments) that these colors would undergo the largest distortions under the CR modulation. It is thus reasonable to infer that the CR modulation would be less noticeable if applied to scenes contained less or none saturated red components.

When fluorescent lamps were first introduced extensive research investigated the relationship between visual perception and the composition of various white light spectra (more details in chapter 3). It was found that color rendering, more so than color temperature, exhibited a close correlation with perception of brightness such that if two light sources of equal color temperature and light levels were observed, the source with higher CR appeared brighter. These findings from the past became significant in the context of this research because of noteworthy comments from a group of the observers who spontaneously reported to have noticed the lights "brightening up" (when CR was increasing), or "dimming down" (when it was decreasing). These comments suggest that the observers noticed a change in *brightness* and not necessarily a *color* difference. The formal research questionnaire did not ask *what* the observers noticed, but only *if* they noticed any change in the scene and *when* it happened. Therefore these informal reports cannot be taken as results per se, but can be considered noteworthy information regarding brightness and its relation to color rendering when joined with past findings from fluorescent research.

In the case of fluorescent sources, the information above is probably more important to the lamp maker than to the lamp user, since for the user, it is probably more significant to know the overall performance of the lamp. After all, a fluorescent lamp comes ready from factory, and all controllability is restricted to dimming it down or turning it off. But in the case of LEDs the situation is different because the users, or lighting professionals, may be the ones defining the spectral mixture, and consequently all chromatic aspects of the white light. Therefore users and lighting designers would like to receive guidelines for implementing the controllability of LED systems in practice; and to optimize performance indices. One of the goals of this thesis research is to provide valid useful information for the lighting community about LED controllability and it becomes important to speculate how to extrapolate the results into real life and apply the data to real architectural scenarios.

7.1. PRACTICAL APPLICATIONS: EXAMPLES AND SPECULATIONS

Perhaps a direct manner of discussing the applicability of the research findings is to envision a practical application of a LED lighting system successfully implementing the CR modulation control strategy. Three hypothetical architectural scenarios will be presented as examples: (1) a corridor; (2) an office space, and (3) a retail store. All three scenarios are examples where color rendering modulation occurs in response to occupation and activities in space. The corridor and office examples can be thought as having a high likelihood of attaining energy savings from applying the technique; on the other hand, the retail scenario is an example where successful implementation of such strategy would be more challenging, and savings would be limited. In the following speculative examples it is important to think not only in terms of *what* type of architectural settings but also in terms of *how* the spaces are used. In general, interiors that are open-public spaces decorated with sparse red components are the most obvious candidates for successful energy savings if such spaces have large unoccupied areas for a considerable amount of time.

Note that the examples are not meant to be strictly realistic, but rather to illustrate the dynamic and reactive nature of the proposed lighting system in view of the results obtained from the psychophysical experiments. The notable point is that lumen levels stay constant and the different lighting schemes can smoothly transition without creating any apparent distraction. Essentially, the lighting technique proposed is one of adjusting zones of a large common space to various levels of lighting quality depending on whether those zones are occupied, strategically proximal to occupied zones or distant from occupied zones.

7.1.1. System's Components

In order to understand the implementation of a LED lighting system employing the CR modulation control strategy it is important to have a realistic idea of its basic components, i.e. LED panels, controller and sensor network, which are described as follows.

LED Ceiling Panels

The LED ceiling panels would be an assembly of LED modules, each containing four RYGB monochromatic LED individually controlled and powered, such that the composite output spectrum could be balanced via preprogrammed strategies. The controller operates LED modules in conjunction with a network of sensors and a communication network. The LED modules are the lowest level of the hardware hierarchy, and are to be assembled within a modular structure of LED panels, defined according to the architectural space.

Configurable Software

A key component of the control system is the software that intelligently links human occupation to the light quality output from LED panels. This software will perform the functions of: (a) Processing sensor data and recognizing activities; (b) Relating activities to the lighting required and to energy conservation; (c) Controlling each of the LED ceiling panels, through algorithms that implement the decision function concerning lighting quality and energy conservation. An important aspect of the proposed control is the assignment of 'light quality zones'. A light quality zone would be a subset of the LED panels designated on the basis of lighting constraints. Typical zones of an office environment could be: reception, primary circulation paths, working areas. The different lighting schemes (combinations of lighting parameters, especially CR) would transition across multiple zones. The plan is to facilitate the designation of a preliminary layout of lighting schemes within the space before information from the sensors is used. Each zone would be defined by the activities taking place within it, daylight conditions, or spatial properties, and set up for a range of lighting schemes (from low to high rendering quality) to suit its needs at the lowest possible energy consumption.

Sensor Network

A sensor network for this system would consist of: (a) Sensors, (b) Low level microcontroller, (c) Power supply to sensors, (d) Interconnection of sensors (wired or wireless). A wide variety of relatively inexpensive, easy to configure, fairly informative sensors are increasingly more ubiquitous (Agogino & Granderson, 2002). Sensors deployed inconspicuously in the space could report real time data and have their information synchronized. The sensors could be spatially distributed and synchronized networking algorithms would provide effective occupancy detection given pre-specified activity configuration. It is fair to anticipate that a good number of spaces (such as open office spaces), which have predictable activity/occupation patterns would need less accurate more cost effective sensing capabilities than retail or residential settings where activities are highly unpredictable.

7.1.2. Examples of Application of Control Technique in Architectural Scenarios

The following examples are intended to reflect three types of dynamic occupancy/activity sensing that could be achievable, and to demonstrate how the experimental results could be used in practice. Illumination levels and color temperature are always held constant and only the quality of light (CR) is modified as activity in the space changes. A network of occupancy sensors are spread over the spaces such that the controller intelligence can discriminate where people are and in which direction they are walking. The spaces are divided into 'lighting quality zones' and each zone can operate any of the eleven lighting conditions from table 6.

The same exact CR modulation control technique will be hypothetically implemented for the three different conditions (the corridor, the office space, and the retail store). In principle, a **98 CRI** lamp could be spectrally tuned, preserving CCT and lumen output, to an **85 CRI** mode using only **90%** of initial wattage. Additional gains could be achieved by adjusting to a **70 CRI** mode using approximately **86%** initial wattage or even a **3 CRI** mode using **77%** initial wattage. These values are based on an optimization exercise that assumes the availability of LEDs with any desired spectral characteristics which is generally not the case today, but extension of the arguments to standard commercially available LED types is reasonable.

	INC.	11	10	9	8	7	6	5	4	3	2	1
CRI	98	92	87	80	72	68	65	62	55	48	41	34
lm/W*	273	312	323	334	347	354	362	366	374	386	398	410
Relative Wattage Consumed	n/a	1	0.96	0.93	0.90	0.88	0.86	0.85	0.83	0.81	0.78	0.76

Table 6 – Summarized information concerning eleven LED white composite spectra and incandescent lamp used in psychophysical experiments.

The CR modulation control technique was implemented to generate the eleven LED white spectra used in the psychophysical experiments. For example, spectrum #11 (**92 CRI)** was spectrally tuned, preserving CCT and lumen output, to obtain spectrum #8 (**72 CRI)** using only **90%** of initial wattage. Additional gains were achieved by adjusting spectrum #8 to obtain spectrum #5 (**62 CRI)** using approximately **85%** initial wattage or even to obtain spectrum #1 (**34 CRI)** using **76%** initial wattage. Table 6 illustrates that rebalancing from high CRI (spectrum #11) to low **CRI** (spectrum #1) reduced the wattage to as much as **76%** of the initial wattage with the same lumen output. Detailed information about the LED spectra used in the experiments can be found in chapter 6, but table 6 shows summarized information about the eleven spectra, including color rendering (CRI), color temperature (CCT) and luminous efficacy (lm/W). The efficacy values were calculated with an assumption of equal power efficiency for all colors (which is not yet achieved by semiconductor technology).

Corridor

Consider a 100 ft long by 20 ft wide corridor that supports various types and patterns of pedestrian traffic flow, such as in an airport terminal or a university (figure 43). Along the walls are pieces of artwork that require reasonable CR to be properly appreciated. The length of this corridor is divided into ten equal 'lighting quality zones'. Example traffic patterns are as follows:

- No activity. To accommodate passing traffic in adjoining corridors: use spectrum #11 (92 CRI) in zones A and J, use spectrum #8 (72 CRI) in zones B and I and spectrum #5 (62 CRI) in remaining interior zones.
- Full activity: use spectrum #11 (92 CRI) in all zones at for continuous best color rendering.
- Person enters at zone A, walking at fast pace (obviously not inspecting the artwork): smooth transition to spectrum #8 for two zones ahead of person and one zone behind. Revert to spectra #5 as person passes and is more than one zone away.
- Person walking at slow pace (perhaps mindful of the scenery): smooth transition to spectrum #11 for two zones ahead, one zone behind and use spectra spectrum #8 for third zone ahead.
- Person stops (perhaps focused on art or divertissement): maintain spectrum #11 for two zones on either side of person and spectrum #8 for one additional zone on each side.
- After hours; security and maintenance workers only. Use spectrum #1 during unoccupied periods. Switch to spectrum #5 for brief periods of occupation.

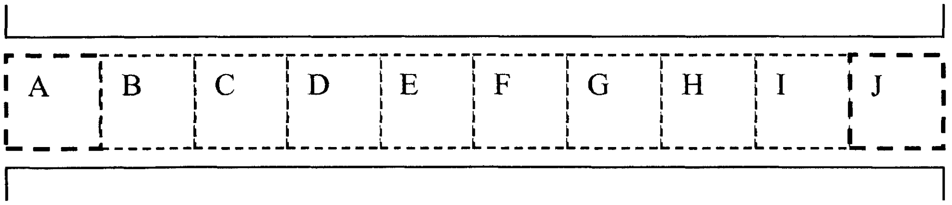


Figure 43 - Hallway divided in ten 'lighting quality zones'.

It is also possible to envision another example of a similar traffic area with same dimensions as the previous corridor but with no paintings on the walls and no specific requirement for color rendering. In this case the control strategy could be executed according to a time schedule with no needs for sensors or advanced controllers. The entire corridor from zones A to J could be set to spectrum #8 during the times of intense traffic, i.e. morning, lunch time and end-of day, and to spectrum #5 for the lower traffic time periods; and the same after-hours scheme as above.

Considering the visual experiences (field of view, velocity and level of visual attention) presented by these hypothetical examples, it is clear that they relate better to the results obtained from the experiments using the 10° field of view. These experiments revealed that saturated red colors suffered the largest and most perceptible color distortions. Also to consider, during these experiments observers were seating quietly specifically looking at the experimental chambers which were predominantly saturated red, and still less than half of the observers noticed any color change at 10°. Therefore we can speculate that while walking in a fast-paced circulation area people would have a determined intentional path in mind and such mind frame would be less inductive of gazing upon details. Consequently a corridor with some colored painting on the walls, but that do not represent a remarkable amount of saturated red components would probably be a space where the CR modulation technique could be implemented unnoticeably.

Office Space

Consider an office space with layout illustrated in figures 44a, 44b & 44c. The area of the office is divided into 16 'lighting quality zones' to employ any of the eleven lighting spectra. The smaller rooms located in the periphery are a conference room and private offices, all with large windows allowing plenty of daylight (zones B through H). Zone **A** corresponds to the reception area, a small room decorated with saturated colors and therefore should permanently use spectrum #11.

The main areas to employ the control technique are designated under zones **I** through **P** which correspond to the open-public part of the office with almost no access to daylight. The space is mainly decorated with light grey and dark green colors, and is organized in islands of cubicles: zones **P** and **I**; **M**, **N** and

O; **J**, **K** and **L**, correspond to three different grouping of people with similar jobs and work schedules. Note that each lighting quality zone (delineated with red squares) is divided into a number of sub-zones (blue squares), which in turn contains four LED panels (grey squares). This granularity allows for more precise control of lighting according to occupancy (see pattern #2). Also note that because of the nature of the space, people will tend to have very predictable patterns of occupation, walking to and from their cubicles. It is therefore fair to assume that, similar to the corridor example above, people will not be too mindful of the details in such circumstances. Examples of possible traffic patterns are as follows:

- Normal week day at 10:00AM: the space is in full activity with most zones occupied. Use spectrum #11 in zone A, and all occupied zones. Use spectrum #8 for periods of time that any zone may be unoccupied.

- Evening after hours: Only some cubicles of zone N are being used (and this zone set to spectrum #11). Zones J, K, L, P and I are set to spectrum #2, while zones M and O are set to spectrum #5. But instead of drastically changing from spectrum #11 to #5 to #2, during the transition of lighting conditions the different rows of sub-zones and panels can be set to gradually change from high to low CR spectra. For instance, looking at zone O, we could think that the first row to the right (neighboring with zone N) is set to spectrum #5, the row to the right to #4 and the third and last row in that zone to #3 which then blends with the first row in zone P, set to spectrum #2.

- Lunch break at about 12 noon: we can assume that zones O and N are occupied and the rest are empty. Use spectrum #11 for zones A, I, O and N; use spectrum #5 for zones J, K, L, M, P.

- Special event on a weekend: such as a training section or seminar taking place at the conference room. Zone P should use spectrum #11, zones O and J spectrum #8 (moving towards changing to settings on zones K and N), zones K, N, M & L should use spectrum #3.

This office example can be related to the results from both the 10° and the 20° psychophysical tests. We should note that during the 20° tests the vast majority of observers did not notice anything at all, even under extremely

Figure 44a – Illustration of a hypothetical interior for office space.

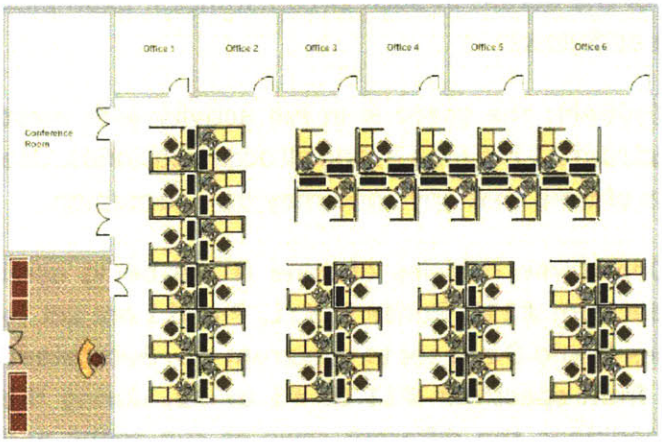


Figure 44b – Floor plan of a hypothetical office space.

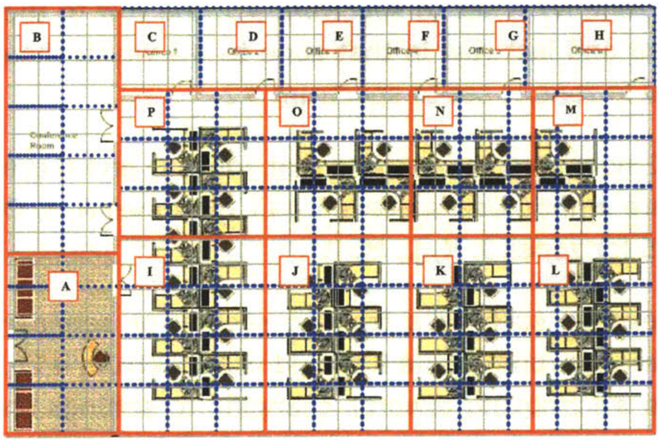


Figure 44C – Layout of ceiling LED system for hypothetical office space: zones (red squares), sub-zones (dotted blue squares) and LED panels (grey squares).

low CR, and considering that fluorescent lamps are available in a range of CRIs from 50, but that typically CRI lower than 70 is unacceptable for most interiors. In such an office environment there are just a few sparse saturated color elements and it is extremely unlikely that there will ever be a predominant saturated red element in such places. Also to consider is the results from all experiments showing no significant difference for sequence modes *increasing* or *decreasing* CR. It is therefore fair to speculate that the color distortions caused by the CR modulation control technique would not be attention grabbing in such spatial circumstances.

Retail Space

Figures 45a, 45b & 45c illustrate a clothing boutique. The area is divided into 6 lighting quality zones to employ any of the eleven lighting spectra. Zones A, B and C receive daylight from the front fully glazed windows.

The space is decorated with colorful surfaces, and is organized in different merchandise areas, such as clothing, jewelry and shoes, all of which are colorful goods. Zone A, B and C must have highest color quality at any time since they are displaying the merchandise to the public through the glazed windows. In the same manner as in the office example, this example uses the hierarchy of lighting quality zone (delineated with red squares) is divided into a number of sub-zones (blue squares), which in turn contains four LED panels (grey squares). Because of the nature of the space, people will tend to have very unpredictable patterns of occupation, as they will move around paying careful attention to the appearance and details of displayed merchandise. Example traffic patterns are as follows:

- Week day at 3:00 PM: a customer walks in and starts to walk towards the clothing displays on right hand-side of the store. It is obvious that all the lighting quality zones on that portion of the store, namely, A, B, C, D and E, must stay on spectrum #11 at all times regardless of the position of the customer. At any moment the person could turn around focusing on a new object. Zones F and G could potentially be shifted to spectrum #8. However, this could be questionable because the customer could quickly turn his/her focus to these areas, which in this case would need to have perfect color rendering. Likewise if someone is at the shoe section it would be questionable to bring zones

D or E to spectrum #8 or #5 for the same reason.

- Week day at 9:00 AM: in the beginning of the day the frequency of customers is slow, and the store stays empty for long periods of time.

Figure 45a – Illustration of a hypothetical interior for retail space.

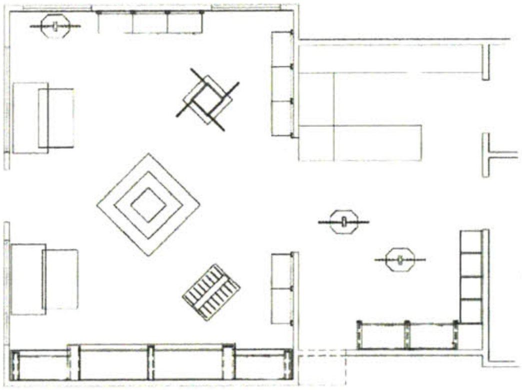


Figure 45b – Floor plan of hypothetical retail space.

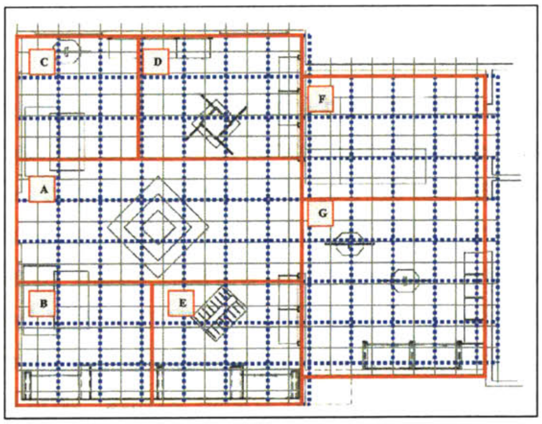


Figure 45c – Layout of ceiling LED system for hypothetical retail space: zones (red squares), sub-zones (dotted blue squares) and LED panels (grey squares).

> In this case, zones F and G could be lit with spectrum #5 and zones E and D with spectrum #8. Zones A, B and C remain at spectrum #11 at all times.

Like the corridor example, this retail example relates more to results from the 10° psychophysical tests, because of the field of view. However the situation here is drastically different because people's states of mind are prone to be more attentive to changes and detail. In such a store environment there are several saturated color elements and it is very likely that subtle changes could be noticed. It is possible to speculate that it would be challenging to have the CR modulation unnoticeable for partially occupied circumstances. The technique would probably be applicable at the F and G during unoccupied periods of time, but even though a slower rate of change should be recommended.

7.1. FUTURE WORK

The results from the experiments provide information about a specific control technique (rebalance of the ratio of red to yellow emissions in search of higher efficacy) examined with respect to one single test field (simulation of real life scene with prominent saturated red components). The test scene for instance was intentionally designed to contain prominent saturated red components, knowing (from the baseline experiments) that these colors would undergo the largest distortions under the CR modulation. It would certainly to be greatly beneficial to test other types of scenes containing less or no saturated red components and other ranges of colors. Another important question that arose from the experiments' results concerns the difference brightness and color perception. Some results from pilot experiments and unsolicited reports from observers suggest that observers noticed a change in *brightness* more so than a *color* difference under changing color rendering. These informal reports combined with some evidence from previous research are an indication for future investigations, that, brightness perception should be investigated in isolation from color perception.

Another constructive investigation would be to test the impact of daylight in color rendering when used in architectural space in conjunction with artificial lighting. Considering a certain amount and quality of daylight, the main research question would be, whether it would be able to provide acceptable color rendering to colorful surfaces, so that the artificial lighting could have its CR lowered without adversely affecting color appearance. This would be in fact a complex research project, but if favorable, it would suggest that in certain day-lit spaces, artificial lights could be tuned to lowest color rendering/highest efficiency mode with no loss in visual quality. This is strong statement.

It was interesting to note from the experiments' results that the lowest acceptable CRI in 10° field of vision was in the range of 70-75. Fluorescent lamps are available in a range of CRIs from 50 and up, the lowest CRI that is very popular is in the range of 75. The spectrum of one of the most popular high color rendering fluorescent lamps (i.e. the tri-phosphor lamp) differs from the LED spectra used in the experiments, and therefore it would be hard to say if these results are related or independent. It would be useful to see how well this relation holds over a variety of different spectral forms, but running a series of visual perception experiments whereby the spectrum of a typical tri-phosphor fluorescent lamp is compared with various different types of multi-chip LED spectral distribution.

As shown in this research and in previous work of the same nature, the evaluation of the chromatic aspects of light sources is a rather complex phenomenon, and in fact the perception of CR change could be thought as an even more complicated issue, if we consider that, in real life, colors stand in a complex relation to one to another, and that perception is connected to visual attention. An ambitious next step for this research could be implementing a real life LED lighting installation (an open-office space would be a good candidate) equipped with sensors and controllers so that the modulating color rendering control strategy could fully tested and the potential for energy savings truly measured.

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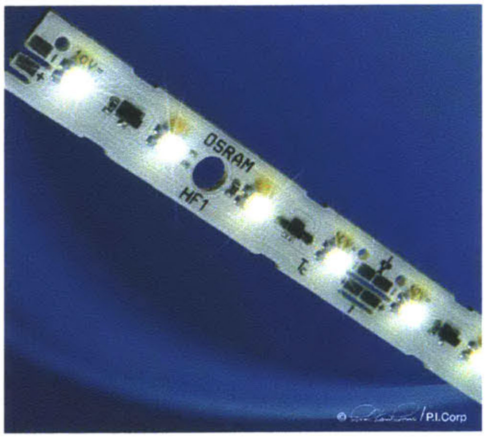
APPENDIX

DATA SHEET - LED MODULE

Product Information Bulletin

LINEARlight

LED Modules



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The OSRAM SYLVANIA LINEARlight LED modules open new creative design options.

Light Emitting Diodes (LEDs) offer substantially better energy consumption than traditional incandescent lamps. These modules can be used wherever temperature or space limitations prevent the use of conventional means of illumination.

Linear modules in particular are being used to inject light into plastics and to mark pathways and outlines. They are designed for an operating voltage of 10.5 Volts and are available in super red, amber red, orange, yellow, true green, blue and white.

OPTOTRONIC® power supplies from OSRAM SYLVANIA are specially designed to operate the LINEARlight modules. A wide range of 10.5V power supplies are available.

- Long life: Up to 100,000 hours depending on color. New HOW2 white modules service life is up to 50,000 hours.*
- OSRAM Power TOPLED® allows high luminous flux
- 120° viewing angle per LED
- Entire strip consists of 32 LEDs
- Size of entire module (L x W) 1.47 ft. x 0.4 in. (448mm x 10mm)
- Size of smallest unit (L x W) 2.2 in. x 0.4 in. (56mm x 10mm)
- Available in various colors: super red, amber red, true green, blue, orange, yellow and white
- Optimal operation with OPTOTRONIC® OT 10.5V power supplies (Literature code ECS049)
- Minimal heat generation
- Extremely low profile (<4mm)
- Up to three modules can be used in a row
- Optics and connector accessories are available (contact OSRAM SYLVANIA)

* When temperature at the Tc point is maintained at 40°C

Product Availability

Product	Color
LINEAR/633/OS/LM01A/S1	Super Red
LINEAR/615/OS/LM01A/A1	Amber Red
LINEAR/610/OS/LM01A/O1	Orange
LINEAR/587/OS/LM01A/Y2	Yellow
LINEAR/525/OS/LM01A/T2	True Green
LINEAR/470/OS/LM01A/B1	Blue
LINEAR/OS/LM01A/W	White
LINEAR/OS/LM01A/HOW2-847	White
LINEAR/OS/LM01A/HOW2-854	White
LINEAR/OS/LM01A/HOW2-865	White

Application Information

Applications

Escape route marker
Border marker
Walkways
Outlines

Application Notes

1. Small dimensions
2. Shock resistance
3. High color efficiency
4. Directional radiation characteristics
5. No IR/UV radiation
6. Edge-lit signs
7. Power supplies for operation
8. General lighting

SEE THE WORLD IN A NEW LIGHT OSRAM

SAMPLE - QUESTIONNAIRE

VISUAL EXPERIMENT

SECTION 1 – EVALUATION 1

Please compare the color chart in Booth #1 with the color chart in Booth #2.

Please rate your comparison by marking the blank chart bellow:

1 LOOK THE SAME
2 JUST NOTICEABLE DIFFERENCE
3 DIFFERENT
4 VERY DIFFERENT

A	B
☐	☐
☐	☐
☐	☐

SAMPLE - QUESTIONNAIRE

EXAMPLE QUESTIONNAIRE USED FOR FOVEAL TESTS

SECTION 2A – Chamber #2.

Question 1: There may or may not have been a change in the appearance of objects in chamber #2. Did you notice any change in chamber #2?

YES	NO

Question 2: If you answered YES,
When did you first notice a change? Was it in the **beginning**, **middle** or **end** of the section?

SAMPLE - QUESTIONNAIRE

EXAMPLE QUESTIONNAIRE USED FOR 10° & 20° TESTS

SECTION 1A – Chambers #1 and #2.

Please do not look back into the Chambers.

Question 1: There may or may not have been a change in the appearance of objects in chamber #1 or in chamber #2. Did you notice any change in chamber #1 or in chamber #2?

YES	**NO**

Question 2: If you answered YES,
- In which chamber did you notice a change?

CHAMBER #1	**CHAMBER #2**

- When did you **first** notice a change? Was it in the **beginning**, **middle** or **end** of the section?