INVESTIGATING THE INFLUENCE OF SPECTRAL POWER DISTRIBUTION CHARACTERISTICS ON HUE DIFFERENTIATION TASK PERFORMANCE

A Master's Thesis

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İHSAN DOĞRAMACI BİLKENT UNIVERSITY

May 2018

I certify that I have read this thesis and have found that it is fully adequate, in scope and in quality, as a thesis for the degree of master of Fine Arts in Interior Architecture and Environmental Design.

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ABSTRACT

INVESTIGATING THE INFLUENCE OF SPECTRAL POWER DISTRIBUTION CHARACTERISTICS ON HUE DIFFERENTIATION TASK PERFORMANCE

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This thesis investigates the effects of spectral power distribution (SPD) characteristics of light sources on hue differentiation performance of observers. Color differentiation efficiency of light sources was investigated with respect to their SPD characteristics. Hue attribute of Kürkçü's (2017) differentiation task was used in this study. Three different groups of students performed the hue differentiation task under 3 different lighting settings; D65, Light Emitting Diode (LED) and Compact Fluorescent Light (CFL) with

4000K and 6500K Correlated Color Temperatures (CCT). The speed and accuracy of performing the hue differentiation task were investigated to indicate the task performance. Ninety students from different departments at Bilkent University and Middle East Technical University voluntarily participated in this study. The participants performed the hue differentiation task inside a light booth as a control light condition. Additionally, the alertness level of the participants as a biological effect of light sources was also investigated in this study. The alertness level of participants was assessed using Karolinska Sleepiness Scale (KSS). The results showed that SPD characteristic of the light sources was effective on hue differentiation performance of observers. Indeed, the hue differentiation performance was in proportion to the radiation intensity of the SPDs of light sources. Overall accuracy and speed of D65 were significantly better in pairwise comparison with LED and CFL due to wide and continuous band SPD characteristic. Moreover, under LED light source the accuracy of Green to Blue (G to B) hue differentiation task was lower in comparison to other hue tasks. However, under CFL the accuracy of Red to Yellow (R to Y) hue differentiation task was lower in comparison to other hue tasks. It was found that alertness level and perceived performance of the participants were not significantly different under different light sources.

Keywords: Spectral Power Distribution (SPD), Hue Differentiation Task, Alertness level, Task Performance

ÖZET

SPEKTRAL GÜÇ DAĞITIMI ÖZELLİKLERİNİN RENK TÜRÜ AYRIMCILIK IŞI UZERINDEKI ETKİNLİKLERİNİN ARAŞTIRILMASI

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Mayis, 2018

Bu tezin amacı, ışık kaynaklarının spektral güç dağılımı özelliklerinin gözlemcilerin renk türü ayrımcılık performansı üzerine etkilerini araştırmaktır. Işık kaynaklarının renk ayrımcılık verimliliği spektral güç dağılımı özelliklerine göre incelenmiştir. Bu çalışmada Kürkçü'nün (2017) renk işi uygulama modelinin, renk türü özniteliği kullanılmıştır. Üç farklı öğrenci grubu, renk türü ayrımı işini üç farklı aydinlatma ayarı altında gerçekleştirdi; D65, LED ve Kompakt Floresan Işığı ile 4000K ve 6500K Renk Sıcaklığı (CCT). Renk türü ayırt etme işini gerçekleştirmenin hızı ve doğruluğu, iş performansını belirtmek için incelenmiştir. Bu çalışmaya, Bilkent Üniversitesi ve Orta Doğu Teknik Üniversitesi farklı bölümlerinden 90 öğrenci gönüllü olarak katıldı. Katılımcılar, bir ışık kabini araciligiyla renk türü ayırt etme işini gerçekleştirdiler. Katılımcıların uyanıklık düzeyi “Karolinska Sleepiness Scale” kullanılarak değerlendirildi. Sonuçlar, ışık kaynağının spektral güç dağılımı özelliğinin gözlemcilerin renk türü ayırt etme performansı üzerinde etkili olduğunu gosterdi. Renk türü ayrımcılığı performansı, ışık kaynakları spektral güç dağılımlarinin radyasyon yoğunluğuyla orantılıydı. D65 genel doğruluğu ve hızı, geniş ve sürekli spektral güç dağılımi nedeniyle LED ve CFL ile çift karşılaştırmada anlamlı derecede daha iyi idi. Üstelik, LED ışık kaynağı altında Yeşil-Mavi renk türü görevinin doğruluğu diğer renk türü görevlerine kıyasla daha düşüktü. Bununla birlikte, Kompakt Floresan Işığı altında Kırmızı-Sarı renk türü görevi, diğer renk türü görevlerine kıyasla daha düşüktü. Katılımcıların uyanıklık seviyesi ve algılanan performansının farklı ışık kaynakları altında önemli ölçüde farklı olmadığı bulundu.

Anahtar Kelimeler: Spektral Güç Dağılımı (SPD), Renk türü Ayırt Etme İşi, Uyanıklık düzeyi, İş Performancı

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CHAPTER I

This chapter contains a brief introduction, the aim of the study and the structure of the thesis. In the introduction part, general information about importance of lighting design and the Spectral Power Distribution (SPD) characteristics of light sources are covered. In the second part, the aim of the study is explained. Finally, in the structure of the thesis part, information about the contents of each chapter is covered.

INTRODUCTION

Nowadays in developed countries, people spend most of their time in workspaces. Therefore, physical factors and ergonomics of workspaces should be designed properly in order to enhance work productivity (Boyce, 2014). Artificial lighting and daylight must be installed with utmost precision to provide proper conditions for seeing and performing the work-related tasks accurately in workspace environments. Proper lighting not only affects occupants' health, general well-being, and mood positively but also leads to better work performance, better safety, fewer errors, and lower absenteeism (Bellia et al., 2011; van Bommel & van den Beld, 2004). Considering these points, recently lighting design studies became the center of attention of most researchers and interior architects to enhance work productivity and visual performances.

There is an important relationship between lighting and work productivity. Lighting affects human task performances visually and non-visually through the visual system, the circadian timing system, and emotion (Boyce, 2014; Rea, 2000). Light source parameters such as illuminance, Correlated Color Temperature (CCT) and Spectral Power Distribution (SPD) are the main factors that can affect the visual task performances. Consequently, quantity and quality of the light source must be considered regarding the particular visual task to be done in work environment. For instance, color oriented tasks are in the category of difficult visual tasks and most affected by the quality characteristics of light sources (Van Bommel & Van den Beld, 2004; Holtzschue, 2012). This is because color quality characteristics of light sources can alter the way that human visual system observes the color of the illuminated objects. Besides, there is a need for the observation of small color differences in some of the color oriented visual tasks which are effective from quality characteristic of illuminated light source. In these tasks, the color differentiation property of the light source, surface reflectance of the visual stimuli and the human visual system play an important role all together (Hashimoto & Nayatani, 1994, Bodrogi et al., 2013). Moreover, light source characteristics also have non-visual biological effects on human visual system. Non-visual biological effects of light sources are through circadian timing system and emotion. According to Campell et al., (1995) light source characteristics affect the suppression of the hormone melatonin which leads to increase or decrease in alertness level.

According to US Department of Energy, SPD is the building block of all color considerations (US Department of Energy, 2016). Considering the trichromatic nature of the human visual system, one can see all the white lights as the same. Distinctly, white light of different light sources with the same appearance can consist of different spectral power distributions. These differences can affect visual performances especially the appearance of the colored objects. There are studies that have investigated the effects of light sources' SPD characteristics on preference, brightness, fidelity, and visibility of objects. However, there is still a need for understanding the effects of different type of light sources with different SPD characteristics on hue differentiation performance of the observers. Additionally precisely investigating the wavelength-band of different type of light sources and their properties to evaluate hue color differentiation in workspaces and its effectiveness on alertness level is important. Considering these issues, this study focuses on investigating the effects SPD characteristics of different type of light sources; Light Emitting Diode (LED), Compact Fluorescent Light (CFL), and Daylight simulator (D65) on hue differentiation performance and alertness level of observers.

1.1. Aim of the study

The main contribution of this study is to investigate the effects of Spectral Power Distribution (SPD) characteristics of light sources on the observer's hue differentiation performance. The sub-aims of this study are identifying the desired bandwidth and feature of SPD in order to obtain higher hue differentiation performance and alertness levels in workspaces with more precise analyses. In the literature, there are numerous, experimental studies on the effects of light source characteristics on different visual performances. However, the effects of different SPDs on hue differentiation performance and alertness level of participants in a controlled lighting condition have not been investigated in the literature. Consequently, this study can be beneficial for filling the gap in the literature. Comprehending the features of light sources SPD in terms of color task performance can help us to provide proficient working spaces that enhance worker's well-being, productivity, and satisfaction both physically and psychologically.

1.2. Structure of the thesis

The structure of the thesis consists of five different chapters. The first chapter consists of introduction, the aim of the study and the structure of the thesis. The introduction part consists of information about the importance of lighting design and light source characteristics for improving performances in workspaces especially in performing color-oriented tasks. In addition, the importance of SPD characteristic of light sources in visual performances is explained.

The second chapter explains the triple factors of seeing and discriminating an object's hue which are the human visual system, lighting, and color. The first part of this chapter starts with explanations about the human visual system's structure and its characteristics. The second part of this chapter consists of information about light parameters and explanations of previous studies about SPD characteristic of light sources. The third part of this chapter describes non-visual biological effects of light sources. Finally, fourth and fifth parts of the chapter two consist of describing color as visual stimuli and color task performances.

The third chapter is on the experimental study of the thesis that is the main part of the study. The first part of this chapter describes the aim of the study, research questions, and hypotheses. Then the second part of the chapter contains information of describing the method of the thesis that consists of the experimental setup, phases of the experiment and demographic information of the participants. The third part of this chapter clarifies the results of statistical data analyses of the experimental study that were conducted with IBM SPSS program. The last part is the discussion part of the thesis that explains the results of this study in comparison or in association with the information in the literature.

The last chapter of the thesis concludes results of the study. Besides, in this chapter strength points, limitations and studies for future investigations are mentioned.

CHAPTER II

Chapter II presents the literature review in accordance with the topic of the thesis. The literature review presents information about the visual system, lighting, color as visual stimuli, and color task performance. In the visual system part, the structure of the human visual system and its operation with light are explained. In the lighting part, light parameters and its effects on the visual performances are clarified. In addition, previous studies on the effects of Spectral Power Distribution (SPD) characteristics on visual performances are covered. In the color as visual stimuli and color task performance part, fundamentals of color and previous studies on color and visual task performances are presented.

VISUAL SYSTEM, LIGHTING AND COLOR TASK PERFORMANCE

2.1. Human Visual System

The human visual system operates with light. Light enters the retina through cornea and lens in the visual system. Retina transmits and converts light into electrical signals. The retina has a multilayered complex structure. It consists of three layers: layer of collector cells, layer of ganglion cells and layer of visual photoreceptors. Layer of collector cells produces the network between photoreceptors while layer of ganglion cells produces non-visual biological system. Light passes through ganglion and collector cells then reaches the visual photoreceptors. Layer of visual photoreceptors consists of four types. The four types of visual photoreceptors inside the retina are grouped into cones and rods, the sensitivity of which can change with the wavelength and color of the light (Egan, 1983; Boyce, 2014). Rods (scotopic spectral) provide night vision and are sensitive in the low-level light situation. Rod photoreceptors are the same and contain the same photo pigment. Due to this reason, rods do not support color vision. Cones (photopic spectral) contain three different photoreceptors and photo pigments. Cone photoreceptors have different but overlapping spectral sensitivities and support color vision (Fisher, 1976; Egan & Olgyay, 2002; Van Bommel & Van den Beld, 2003; Boyce, 2014). The sensitivity of cones are "short wavelength sensitive (S-cones) with the peak at almost 440nm, Middle wavelength sensitive (M-cones) with the peak at 545nm, and Long wavelength sensitive (L-cones) with the peak at 565nm" (see figure 1) (Boyce, 2014, p.48).

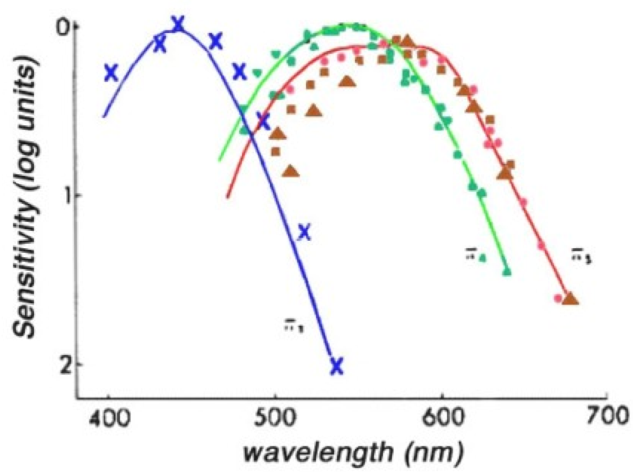

Figure 1: Cone photoreceptors: Blue, Short wavelength. Green, Middle wavelength. Red, Long wavelength

(Source: Fisher, G. H. (1976). The perception of color. *Journal of the Neurological Sciences*, *27*(4), 529–530.)

Comparing two curves of photopic and scotopic spectral curves, we can understand that maximum visual sensitivity of cones in the human visual system lies in the yellow-green (almost 555nm) and rods in the blue-green wavelengths (almost 507nm). The human visual system has minimum sensitivity to blue and red wavelengths (see figure 2) (Egan, 1983; Van Bommel & Van den Beld, 2003; Boyce, 2014).

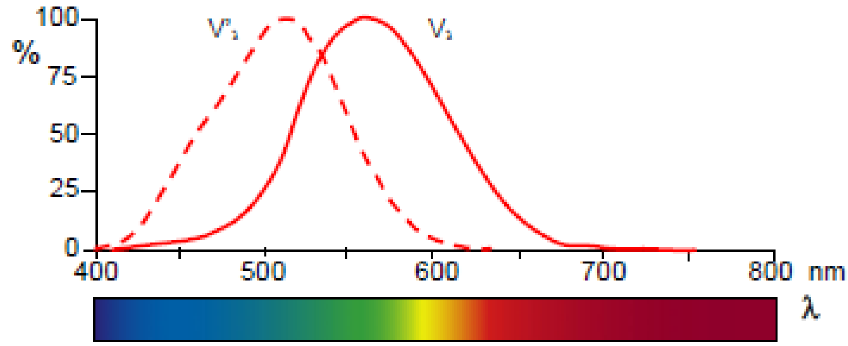

Figure 2: Photopic and Scotopic curves: Solid line, Cone system and Dashed line, Rods system

(Source: van Bommel, W., & van den Beld, G. (2004). Lighting for work: a review of visual and biological effects. *Lighting Research & Technology*, *36*(4), 255–266)

Consequently, color vision of the human eye is a trichromatic system that is based on three different cone photoreceptors. The human visual system interprets the light with a single or limited number of wavelengths as a certain color and interprets white light while the light consists of all visible wavelengths. The light source with a single wavelength is specified as monochromatic light (Boyce, 2014). While daylight or any other light source illuminates an object, certain wavelengths of the light are absorbed while others are reflected. The reflected wavelengths lead to the appearance of the object. There is a relationship between wavelengths of the light and appearance of the objects but it is not an absolute relationship because the human color vision system compares the wavelengths coming from different surfaces around the colored object not just the object. Special conditions are required for the color perception of the visual stimuli exactly with the wavelength of the light source (Fisher, 1976; Boyce, 2014).

There is a process in the human visual system that can decrease or increase the sensitivity while it is exposed to light sources with different intensity distributions. This is a wavelength related light adaptation characteristic of the visual system. The sensitivity of the human visual system decreases more while exposed to red light sources, which have more emission in long wavelengths than blue light sources, which have more emission in short wavelengths (Van Bommel & Van den Beld, 2004). The results of a study showed that intensity distribution of light sources affect the relative level of excitation of each type of cones. They used light sources with different intensity distributions and CCTs. Color distinguishing capacity was found better under light source with higher CCT. It was stated that the light sources with spectral peak in blue zone of the intensity distribution lead to higher level of S-cone excitation than lower CCT sources (see figure 3) (Pardo et al., 2012).

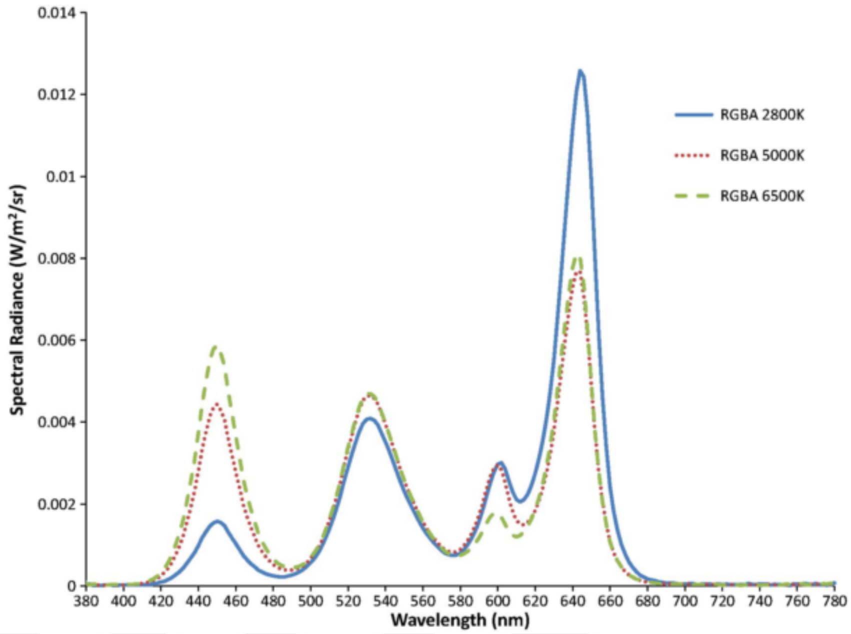

Figure 3: SPD of three different light sources with 2800K, 5000K and 6500K

(Source: Pardo, P. J., Cordero, E. M., Suero, M. I., & Pérez, Á. L. (2012). Influence of the correlated color temperature of a light source on the color discrimination capacity of the observer. *Journal of the Optical Society of America A*, *29*(2), A209)

2.2. Light source parameters

The illumination may be daylight, electric light, or a combination of them in workspaces. Artificial and electrical lighting in the workspace must be installed with precision decisions with respect to lighting parameters. Proper electrical lighting must fulfill both the quantity and quality requirements according to the specific task in workspaces. Sufficient luminous and the color of the light should be provided according to the visual performance as these factors affect the appearance of the work instruments (Rea, 2000; Ural & Yilmazer, 2010). Consequently, consideration of spectral composition, light direction and other parameters of the light source are required for having the demanded effect in terms of aesthetics, ergonomics, and atmosphere, energy and these lead to increase in productivity, health and well-being of workers (Schupbach et al., 2015).

Illuminance, Correlated Color Temperature (CCT), Color Rendering Index (CRI) and Spectral Power Distribution (SPD) are vital lighting parameters that most affect the visual performances. Illuminance of the light source is the quantitative aspect of light source characteristics. It is the amount of light on a horizontal plane. Good color visibility requires the proper amount of illuminance in workspaces (Holtzschue, 2012). This is because, insufficient illuminance would lead improper perceiving the exact color of the illuminated objects and high amount of it would lead to glare. For instance, eight percent improvement is observed in work productivity with increasing the illuminance level from 300 to 500 lux in an industrial environment. Thus, it can be derived that sufficient illuminance level for industrial work environments is almost 500 lux (Rea, 2000; van Bommel & van den Beld, 2004).

There are many different beliefs about the effects of light and color on preference and perception (Davis & Ginthner, 1990). It is commonly known that people prefer low color temperature light sources at low illuminance levels for relaxing atmosphere and high color temperature light sources at high illuminance levels for working environments (Boer & Fischer, 1981). In addition to experimental studies for comfortability Kruithof curve is used as a graph that shows preferred combination of illuminance and correlate color temperature (CCT) for interior spaces. Kruithof curve shows the preferred illuminance level range for specific CCTs of light sources. For instance, “warm fluorescent lamps at 3000K would be preferred at 500 to 2500lux, whereas cool fluorescent lamps at 4200K would be preferred at 70 lux and above" (see figure 4) (Kruithof, 1941, p.69). Besides, Kruithof explains that appearance of light sources at range of low illuminance level with high CCT is blue and called dim or cold while at range of high illuminance level with low CCT is red and called unnatural or undesirable (see figure 5) (Kruithof, 1941; Fotios, 2017).

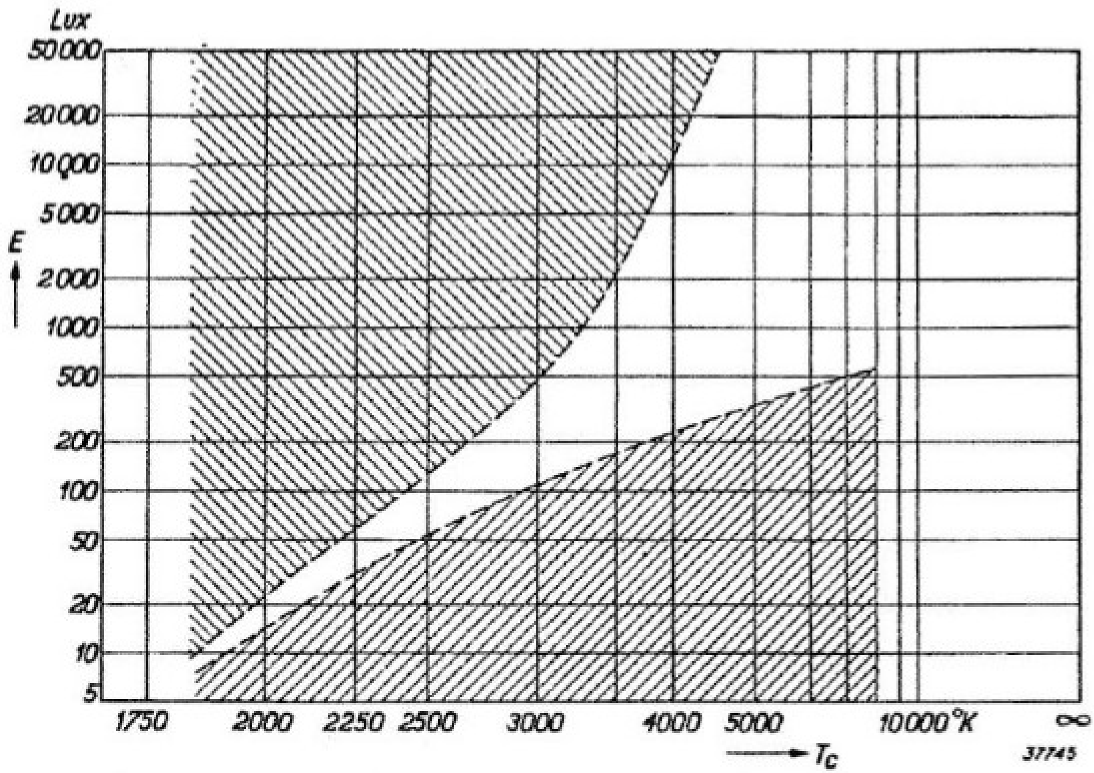

Figure 4: The original version of Kruithof curve

(Source: Kruithof A., A. 1941. Tubular luminescence lamps for general illumination. Philips Tech Rev. 6(3):65–73.)

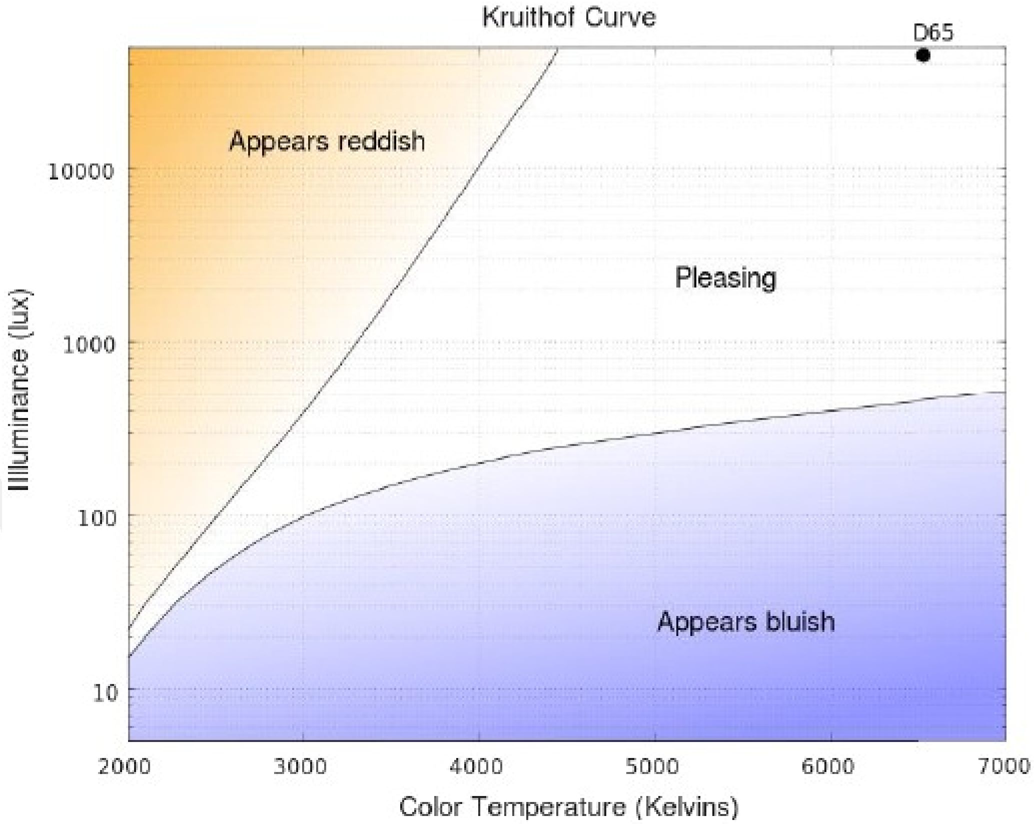

Figure 5: The modern version of Kruithof curve.

(Source: http://en.wikipedia.org/wiki/File:Kruithof_curve_2.svg)

Additionally the energy efficiency factor of the lights sources must consider for workspaces (Yilmazer et al., 2009). In a study conducted by Manav et al., (2014) stated that tubular LED lamp gives higher energy performance and higher visual comfort satisfaction while compared to tubular fluorescent light sources in workspaces. They investigated the energy efficiency, visual comfort and light quality of tubular fluorescent and LED lamps.

2.2.1. Correlated Color Temperature (CCT)

Correlated Color Temperature (CCT) is a metric that relates to the color appearance of the emitted light. It does not demonstrate the color of the illuminated object. CCT is given in Kelvin (K) and the light source color changes according to the value of kelvin. Lower Kelvins appear warm and higher values of Kelvins appear cool. Hence, increasing the temperature leads to change in appearance from red followed by yellow and white respectively. For instance, a light source with zero on Kelvin scale appears black, between 1000K and 2000K it appears red, around 2500K warm white followed by 4500K and 6500K that appear cool white and bluish white respectively. For instance, appearance of incandescent light sources is in yellow color the CCT of which is between 2700K and 3300K commonly. CCT of a regular incandescent lamp is 2850K. A cool white fluorescent lamp has a CCT of 4100K (see figure 6) (Nassau, 1998; Elvidge et al., 2010).

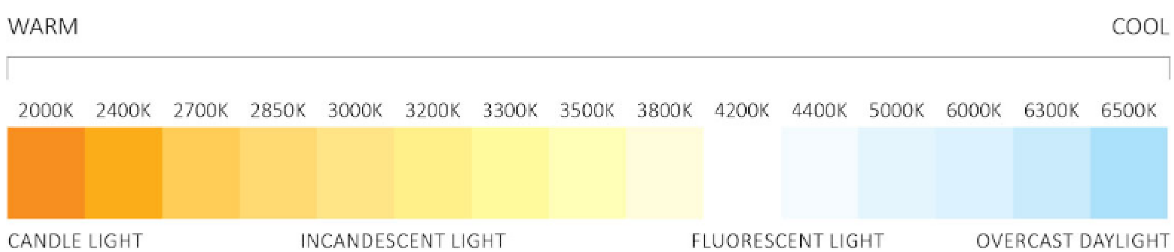

Figure 6: Correlated Color Temperature (CCT) values of different light sources

(Source: https://www.elementalled.com/correlated-color-temperature)

It is confirmed that different CCTs affect human beings psychologically and physiologically with visual and non-visual processes (Sivaji et al., 2013). Numerous surveys were investigated to understand the effects of CCTs on human behavior, attention, performance, preference, and perception (Harrington, 1954; Steffy, 2002; Huang et al., 2015; Sivaji et al., 2013; Manav, 2007; Kürkçü et al., 2017; Shamsul et al., 2013).

Results of studies conducted by Steffy (2002) and Harrington (1954) showed that higher CCTs gave higher brightness perception and enhanced work performance while comparing 3000K, 3500K and 4000K CCTs. In another study, focused and sustained attentions were observed to be significantly better under 4300K than 6500K (Huang et al., 2015). According to a study, CCT of 4000K (Cool White) was the most comfortable and higher typing speeds was found under 4000K while 6500K (Daylight) was found to be the most preferred CCT of light (Sivaji et al., 2013). The results of a study applied by Manav (2007) showed that 4000K was the preferred CCT by participants regarding impression of spaciousness and comfort. Manav (2007) used 2700K, 4000K and a combination of 2700K and 4000K in her study. In another study, it was found that the accuracy of differentiating the hue and chroma attribute of color in color differentiation tasks was better under 4000K than 2700K. While, the speed of performing the color differentiation tasks was not different under 4000K and 2700K (Kürkçü, 2017). Results of the study conducted by Shamsul et al., (2013) showed that overall participants preferred 4000K (Cool white) than other CCTs. Additionally, in that study the accuracy of the computer-based visual task was observed to be higher under 6500K. Besides, the speed of typing was observed to be better in 4000K and there was no significant difference between the CCTs for paper-based task performance.

2.2.2. Color Rendering Index (CRI)

Another measurement criterion of light source color characteristics is color rendering. It evaluates the appearance of objects under artificial light sources. Light source characteristics can affect color attributes (Hue, Chroma, and Value) of an object. Consequently, color-rendering metric is used to determine these complicated changes in a meaningful way. International commission on illumination (CIE) assessed an internationally used Color-Rendering Index (CRI) for evaluating the color appearance of objects under light source illumination (Davis, 2010).

The Color Rendering Index (CRI) values range from zero to 100, while zero stands for low CRI & 100 indicating the perfect CRI. The CRI of the light sources must be chosen according to the corresponding visual task that will be done under that light source (IESNA, 1993). There is a demand for high CRI value for observation of paintings in museums so light sources with high CRI values must be chosen to illuminate paintings in museums and art galleries (see table 1) (CIE, 1986; Pardo et al., 2012).

Table 1: Proper CRI values for being used in different spaces

(Source: International Commission on Illumination, CIE (1986). *Guide on interior lighting*. Paris: The Commission.)

CRI R_a	Examples of Usage
> 90	Color matching, art galleries
80 – 90	Homes, restaurants, textile industry
60 – 80	Offices, schools, light industry
40 – 60	Heavy industry
20 – 40	Outdoors

Light sources have different CRI values. For instance, Incandescent lights have high CRI values, near 100 but low-pressure sodium lamps as monochromatic light sources have very low values of CRI. Nowadays, LED light source has received much attention considering their long life cycle, low power consumption etc. However, the CRI of LED light sources is lower than that of regular incandescent lamps and this may affect human visual performances regarding visual tasks. Table 2 shows the different lamp types and their generally used CRI and CCT ranges (see table 2) (Hong et al., 2017; Boyce, 2014).

Table 2: CRI and CCT ranges of different type of light sources

(Source: Boyce P. R (2014). *Human Factors in Lighting*.n. p. Boca Raton: CRC Press, Taylor & Francis Group, 2014. p.37)

Light source	Incandescent	Tubular fluorescent	Compact fluorescent	High pressure sodium	White LED (streetlight)	Metal halide
CCT(K)	2500K-2700K	2700K-17000K	2700K-6500K	1900K-2500K	2650K-6500K	3000K-6000K
CRI	100	50-98	80-90	19-83	40-85	60-93

2.2.3. Spectral Power Distribution (SPD)

Spectral Power Distribution (SPD) is another color characteristic of light sources. It describes the amount of radiant power emits by light source at each wavelength or band of wavelengths in the visible region (380 nm to 760 nm) (Rea, 2000). Correlated Color Temperature (CCT) stands for the SPD that is refined with a simple number. According to SPD graph, the sources that emit radiation more strongly at the middle or longer (red) wavelengths appear as warm white and are generally preferred for aesthetic purposes. However, the light sources with shorter wavelengths that appear cool white give an impression of sharper and colder light (Elvidge et al., 2010).

Different types of light sources have different spectral intensities. Light sources with single spectral intensity are monochromatic light sources. Incandescent bulbs and daylight are continuous spectra light sources that cover a relatively large range of wavelengths in their SPD. Furthermore, the line spectra light sources are the ones that have dispersion radiation intensities in their SPD. Gas and electric charge light sources are the examples of line spectra light sources (see figure 7) (Gilchrist & Nobbs, 2017; Boyce, 2014).

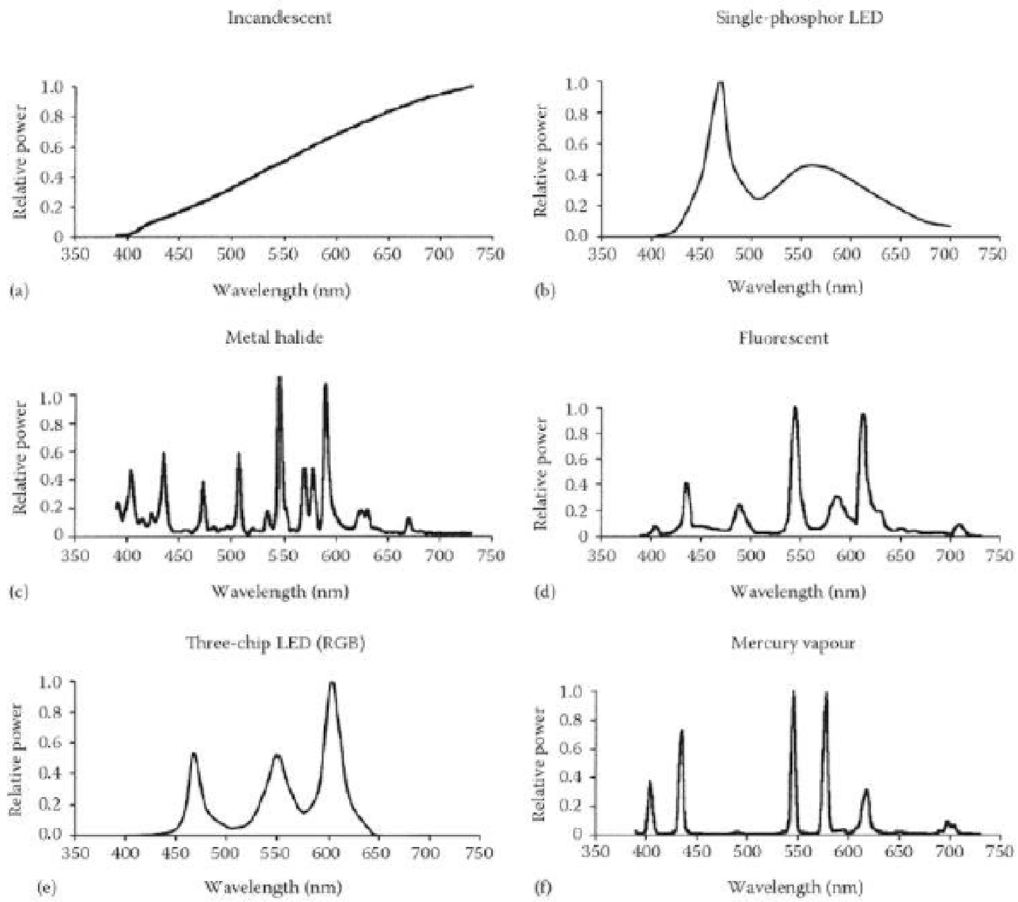

Figure 7: Spectral Power Distribution of different light sources

(Source: Boyce P. R (2014). *Human Factors in Lighting*.n. p. Boca Raton: CRC Press, Taylor & Francis Group, 2014)

Daylight as an example of the continuous spectra light source varies especially in ultraviolet spectral region, due to the function of seasons, time of day, and geographic location (CIE, 1986). Besides, the color temperature of daylight also varies during the day. Color temperature of daylight is lower at sunrise and higher at sunset. Considering this issue, Commission on Illumination (CIE) has defined simulators of the standard daylight illuminants the SPDs of which are defined for color measurement purposes (Nassau, 1998; Cie, 2004). The SPD of simulators is continuous band spectrum but not the same as daylight's SPD. The color temperatures of CIE simulators vary from 4000K to 25000K. The most common illuminant of these simulators is D65, where label D stands for daylight and 65 is the number of the color temperature in hundreds and here stands for 6500K. D65 simulator with filtered fluorescent lamp is now in use regularly for color measurement purposes (see figure 8) (Cie, 2004; Hirschler et al., 2011; Dietz, 2011; Broadbent, 2017; Gilchrist & Nobbs, 2017).

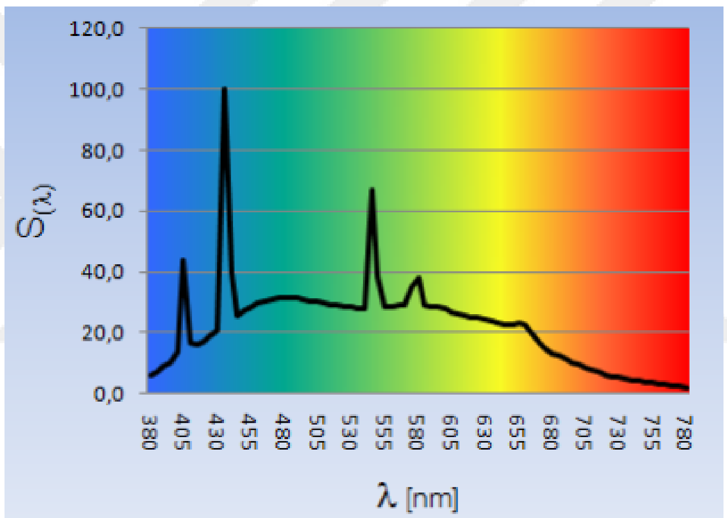

Figure 8: Spectral power distribution of D65 with fluorescent lamp

(Source: Dietz, C. (2011). Light Sources and Illuminants, Color vision and colorimetry: Thero and Applications, Second Edition, 23-39.)

Elvidge et al., (2010) investigated spectral characteristics of light sources for the identification of lighting types. According to their explanations, Compact Fluorescent Lamp (CFL) is a low-pressure gas discharge lamp, which is designed to replace the incandescent light bulbs. Their investigations showed that its SPD is different from that of incandescent light bulbs. Incandescent emits light in a broad continuous spectrum and has a peak emission near the infrared, which is on red rather than green and blue.

However, the SPD characteristic of CFL light source consists of sharp narrow emission lines and is mostly heavy in the short wavelengths (blue) which has no emission in 2500nm (infrared). The highest peak on SPD of CFL means that the color under that peak area is emitted more than other colors of wavelength. The figure below shows that a 13 watt Compact Flourecent lamp (CFL) has two peak lines at 544nm and 611 nm (see figure 9).

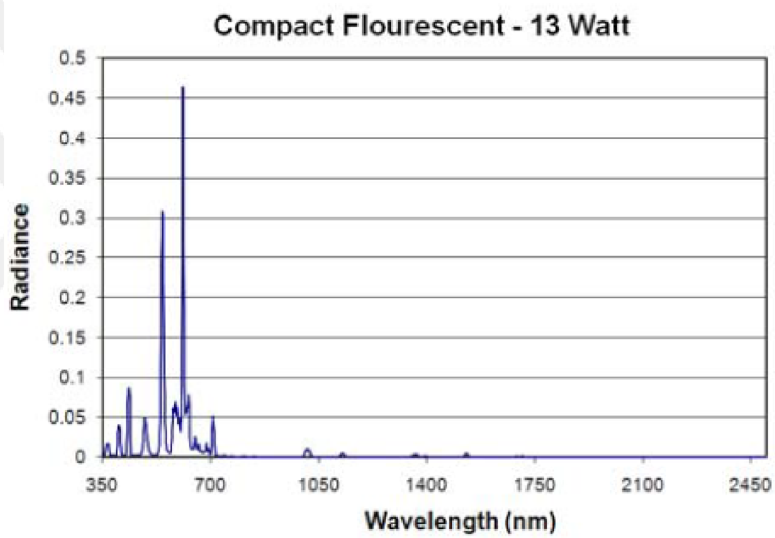

Figure 9: Spectral Power Distribution (SPD) of a 13 watt Compact Fluorescent Light (CFL)

(Source: Elvidge, C. D., Keith, D. M., Tuttle, B. T., & Baugh, K. E. (2010). Spectral identification of lighting type and character. *Sensors*, *10*(4), 3961–3988.)

Light Emitting Diode (LED) is a solid-state light source that generates light by electroluminescence. Incandescent light sources are replaced LED light sources as they are efficient, long lasting, resistant to vibration and provide full spectrum of colors (Schupbach et al., 2015). Elvidge et al (2010) measured the SPD of LEDs with blue, green, orange and red colors. Additionally they measured the SPD of neutral and cool white LED streetlights. The results indicated that the SPD of the neutral white emitted more in the red zone in comparison to cool white LED (see figure 10). In general, the LED spectra have a narrow emission band and have its curve resembling Gaussian curves with two peaks in 'blue' and in the 'green to red' mostly. It does not have emission in the infrared (Boyce, 2014).

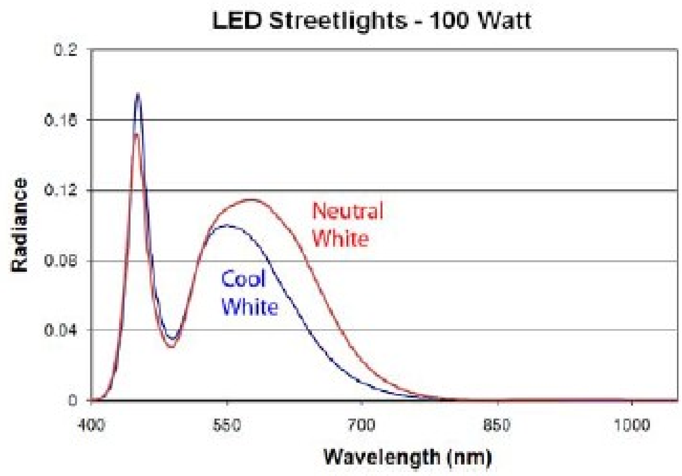

Figure 10: SPD graph of neutral and cool white LED

(Source: Elvidge, C. D., Keith, D. M., Tuttle, B. T., & Baugh, K. E. (2010). Spectral identification of lighting type and character. *Sensors*, *10*(4), 3961–3988.)

Color perception of the stimuli retains the same under different light sources. However, if the light sources consist of different SPDs, the perceived color of the stimuli will not be the same. It is due to the fact that the interaction between SPD of light source, spectral reflectance of the visual stimulus and human eye sensitivity are vital factors which can affect the color appearance of the illuminated objects (Pinto et al., 2010; Pardo et al., 2012). In the literature there are studies that evaluate the effects of these issues on the user perception, appearance of the materials, appraisal of the visual environment, visual performance and preferences (Viénot et al., 2005; Mahler et al., 2009; Bodrogi et al., 2013; Jiang et al.,2014; Schupbach et al., 2015).

Bodrogi et al., (2013) conducted an experimental study with three different light sources; tungsten incandescent lamp (INC, reference), a compact fluorescent lamp (CFL) and a LED lamp with white phosphor. The light sources have different SPDs but almost the same CCT of 2600K. The results showed that INC was better in comparison to CFL and LED regarding color fidelity observations due to its wide and continuous SPD characteristics (see figure 11) (Bodrogi et al., 2013).

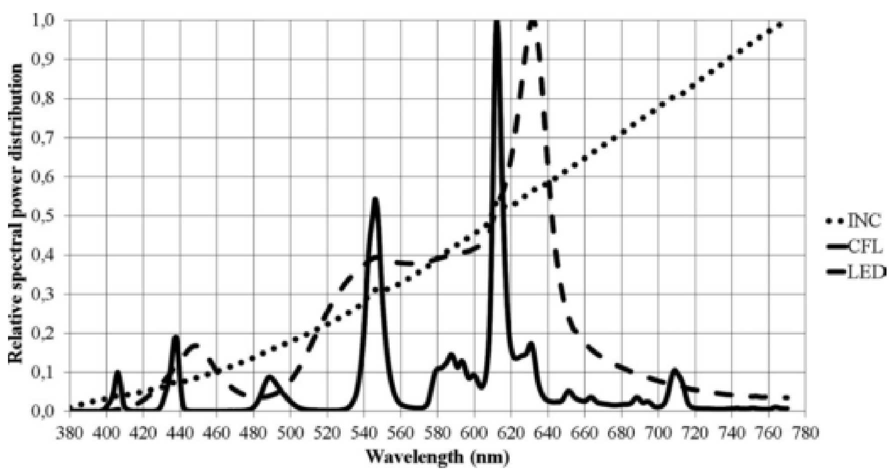

Figure 11 : SPD of INC, CFL and LED light source used in Bodrogi et al.,'s (2013) study.

(Source: Bodrogi, P., Brückner, S., Khanh, T. Q., & Winkler, H. (2013). Visual assessment of light source color quality. *Color Research and Application*, *38*(1), 4–13.)

Another experimental study was conducted to investigate the perception of different materials under different light sources. First part of the study results showed that for some of the materials participants indicated clear preferences. For instance, they preferred red carpet and synthetic materials under warm light whereas blue MDF under cold light. Second experimental part of this study was conducted to understand the effects of different light sources with the same CCT (3000K) on the perception of materials in a semantic differential six-point scale. The light sources were LED light source, high intensity discharge (HID) lamp, fluorescent lamp, and halogen lamp. The results showed that under LED light source, materials appeared softer to the participants than the other light sources. They explained that it was due to the fact that LED light source emits more diffuse light pattern which leads to softening effect (see figure 12) (Schupbach et al., 2015).

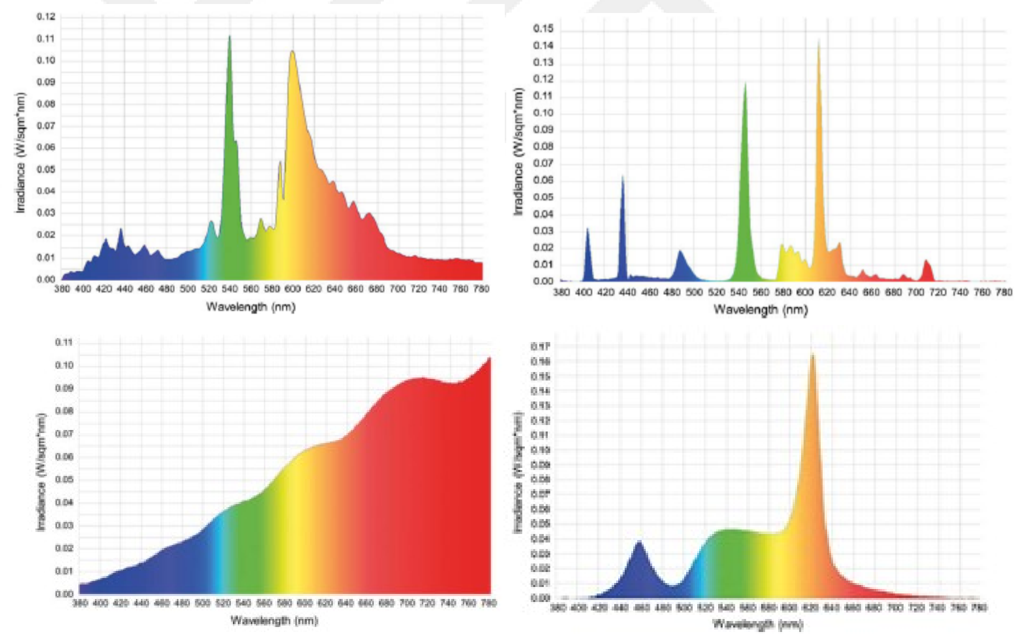

Figure 12: Left top; SPD of HID, Right top; SPD of Fluorescent, Left down; SPD of Halogen, Right down; SPD of RGB LED

(Source: Schupbach, R. L., Reisinger, M., & Schrader, B. (2015). Influence of lighting conditions on the appearance of typical interior materials. *Color Research and Application*, *40*(1), 50–61.)

Additionally the study was applied by Jiang et al., (2014) for investigating the effects of spectrum characteristics of light sources on visual performance at mesopic condition regarding color oriented task. The study was applied using three light sources; High-pressure sodium (HPS), RGB LED and phosphor converted white LED light. The results showed that RGB LED light source gave better-saturated effect to the color and color matching under RGB LED was with less error and less mean time in mesopic condition (low illuminance 20lux, 10lux, 5lux). They explained that the results were due to the three narrow peaks in SPD of RGB LED and one peak, which overlapped the scotopic luminous efficiency at 510 nm. The results of the subjective evaluation showed that under white LED light source colors appeared to be more natural. Besides, error rates were highest under HPS light source regarding color matching due to its narrow band spectrum, which leads to low CRI (see figure 13).

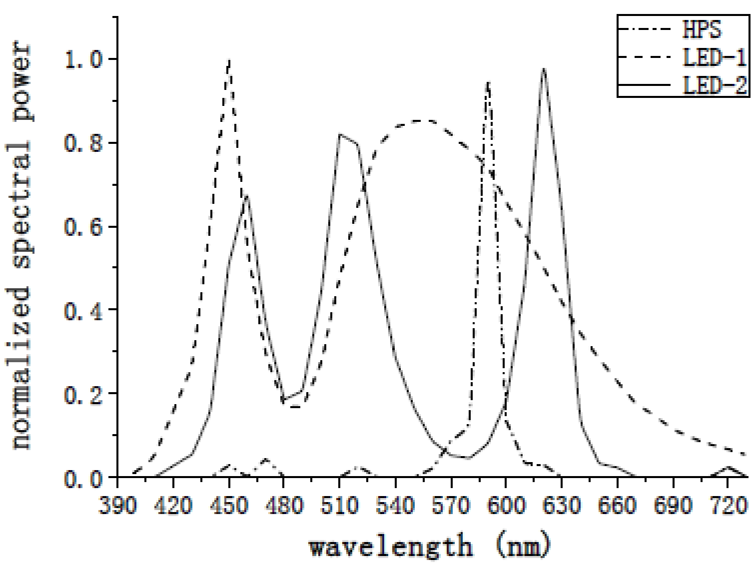

Figure 13: SPD of HPS, RGB LED (LED2) and phosphor converted white LED (LED1)

(Source: Jiang, L., Lei, P., & Jin, P. (2014). Research of Spectrum Effects on Color Visual Performance at Mesopic Condition, 1–4.)

In another study, the results of which is in contrast with the results of the study done by Jiang et al., (2014) error rates in color differentiation task were higher under RGB LED.

They explained that SPD of RGB LED is narrowband spectrum and has three peaks and three downs that lead to low emission in certain zones of the spectrum. The error rates in ordering the caps were higher specifically around greenish-blue and purple shades. This study again confirmed the effectiveness of the SPD characteristics of light sources on the color differentiation capacity of the observers (Viénot et al., 2005; Mahler et al.,2009).

2.3. Biological effects of light sources

Nowadays, the light source quality goes beyond simply affecting the visual performances, it also has biological and behavioral effects. As mentioned earlier the retinal ganglion cell is one of the photoreceptor types in the human visual system. It regulates circadian timing, heart rate, body temperature, melatonin suppression and alertness level as non-visual biological effects of lighting (Zeitzer et al., 2000; Cajochen et al., 2005). The sensitivity of ganglion cell varies with different wavelengths and the color of the light sources and is most sensitive to short wavelength radiations (blue light sources) (Zeitzer et al., 2000; Van Bommel & Van den Beld, 2003; Cajochen et al., 2005; Van Bommel, 2006; ; Bellia et al., 2011).

The proportion of blue and green spectrum of light within its SPD can define the direction of influence which can promote or decrease sleep or alertness level (van Bommel & van den Beld, 2004; Bellia et al.,2011). Exposure to blue light sources that have peak (1-480 nm) in short wavelengths lead to an improvement in mood, alertness level, and visual performance in the human visual system. The SPD of light sources must be managed and balanced in order to adapt to the user’s needs. This aspect has become more important nowadays as the increase in the development of light devices has led to more exposure to non-homogeneous spectral composition of lights (Linhart & Scartezzini, 2011; Bellia et al., 2011; Papamichael et al., 2012; Chang et al., 2013; Bourgin & Hubbard, 2016).

Alertness level as non-visual biological effect of light sources can increase or decrease with the suppression of melatonin hormone. Melatonin is a hormone that alarms the human body to know the time of sleep and wake up. The level of melatonin usually starts to increase from evening until sunset, as the sun goes down and daylight exposure decreases. According to a study which was conducted with healthy male participants, melatonin level of participants decreased significantly while they were exposed to short wavelength monochromatic blue light sources (max 479 nm) in comparison to red light source (max 627 nm) (Papamichael et al., 2012).

According to another study, wavelength of the light source affected subjective alertness levels. Three CCTs 6500K, 2500K and 3000K of compact fluorescent lamp were used in that study. Results showed that under 6500K with low illuminance level (40lux) subjective alertness level and cognitive performance specifically sustained attention were increased significantly in comparison to other CCTs after approximately ninety minutes of exposure to the light. This alerting level was observed to be due to the high amount of blue component in the wavelength composition of 6500K despite the fact that the illuminance level is so low to detect an alerting effect. Their results are in agreement with the studies that support higher sensitivity of human circadian system to short wavelengths (Chellappa et al., 2011; Thapan et al., 2001).

2.4. Color as Visual Stimuli

Physicists explain that color is a function of light. Newton gave names to the seven basic colors of the sunlight wavelengths; red, orange, yellow, green, blue, indigo and violet. Difference between these colors caused by a tint difference in the wavelengths (Aires, 2016). However, color appearance of the objects that are illuminated by light sources is produced through the reflection of wavelength from the objects and their surrounding surfaces.

The surface color of the objects is defined with different color theories. Traditional color theory consists of three pigment colors; red, blue and yellow. These are primary colors and mixtures of the pigments of these colors lead to secondary colors; orange, green and purple. By mixtures of these secondary colors with their adjacent primary colors, tertiary colors are created; red-purple, red-orange, yellow-orange, yellow-green, blue-green and blue-purple. All these 12 colors can be seen in a color wheel (Holtzschue, 2012). The primary colors arranged with equal spaces around the circle wheel. Colors inside the circle represent the mixtures of primary colors. Albert Munsell proposed another color wheel in 1905 which consists of five pigment primary colors; green, blue, purple, red and yellow which he called principle colors (see figure 14 and 15) (Zelanski & Fisher, 2010; Holtzschue, 2012).

Figure 14 : Traditional Color Wheel devised by James Maxwell

(Source: Holtzschue, L. (2012). *Understanding color: an introduction for designers*. Hoboken, New Jersey: John Wiley & Sons.)

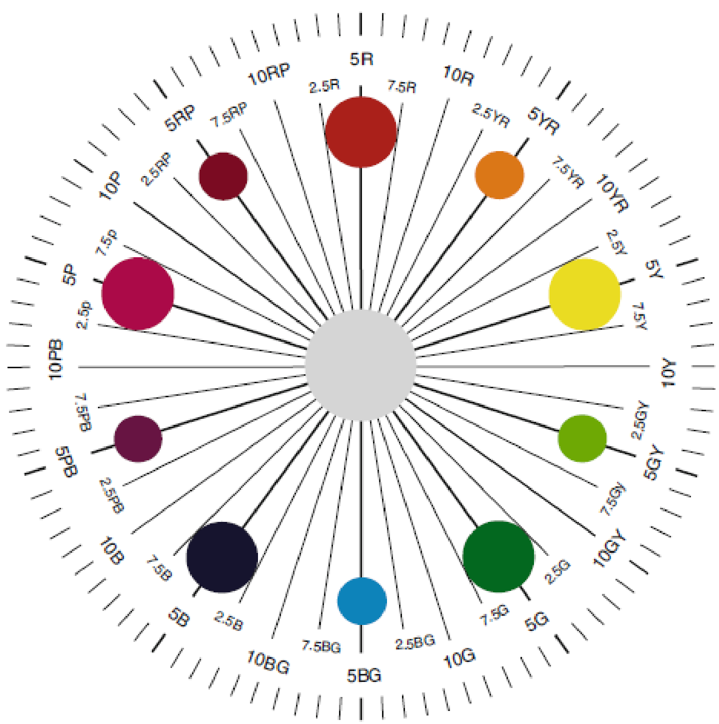

Figure 15: Munsell color wheel with five principle colors and different hues.

(Source: Fisher, G. H. (1976). The perception of color. *Journal of the Neurological Sciences*, *27*(4), 529–530.)

Hue, value and chroma are the three attributes of color that give characteristics to color to distinguish one color from another. Hue is the chromatic pure color attribute, which is named as red, blue, yellow, green, etc. Hue represents the qualitative aspect of color which means the electromagnetic wavelengths of color stimuli same as the one seen in the reflection of sunlight through a prism (Pridmore, 2011). Saturation or chroma is the other attribute that shows the level of saturated color. Two colors can have the same hue but due to different saturation ranges, they are seen differently. Value or lightness is the attribute that shows how much darker or lighter a color is seen (Ferhman & Ferhman, 2000). Chroma and value attributes are quantitative aspects of a color which means the number of identical waves or photons that are presented by color stimuli (Pridmore, 2011).

There are different color order systems for distinguishing the attributes of color; HSB System, The COLORCURVE, CIE Lab System, The DIN (Deutsche Industrie Normung-German Standardization Institute), Hungarian color order system, NCS and Munsell color order systems. Between the different color order systems for color task performances, Munsell color system is the most preferred and acceptable because it is the first which divided the color into hue, value and chroma dimensions and illustrates the color in a three dimensional space (Boyce, 2014; Aires, 2016).

Munsell's color order system was arranged according to the human color vision's trichromatic system. In this three dimensional system, hue is measured along the horizontal circles, chrome going outward in radial manner and value is measured vertically from black to white (Egan, 1983; Aires, 2016). Munsell divided the hues into five equal steps consisting of red (5R), yellow (5Y), green (5G), blue (5B) and purple (5P) and called them principle hues. Intermediate hues are the divisions between each of the principle hues with yellow-red (5YR), green-yellow (5GY), blue-green (5BG), purple-blue (5PB) and red-purple (5RP) names. From this subdivision, Munsell gets 10 division of hue but it may frequently happen that a color does not fall exactly on one of the 10 divisions. Therefore, he made a 100-step scale by dividing the 10 divisions into groups of 10. Value specified on a vertical access and in a numerical scale from1 (black) to 10(white). It is the attribute of the color, which related to the lightness of color. Chroma is related to the saturation attribute of color and its numerical value is from 0 to various maximum values (see figure16) (Fisher, 1976; Nassau,1997; Boyce, 2014).

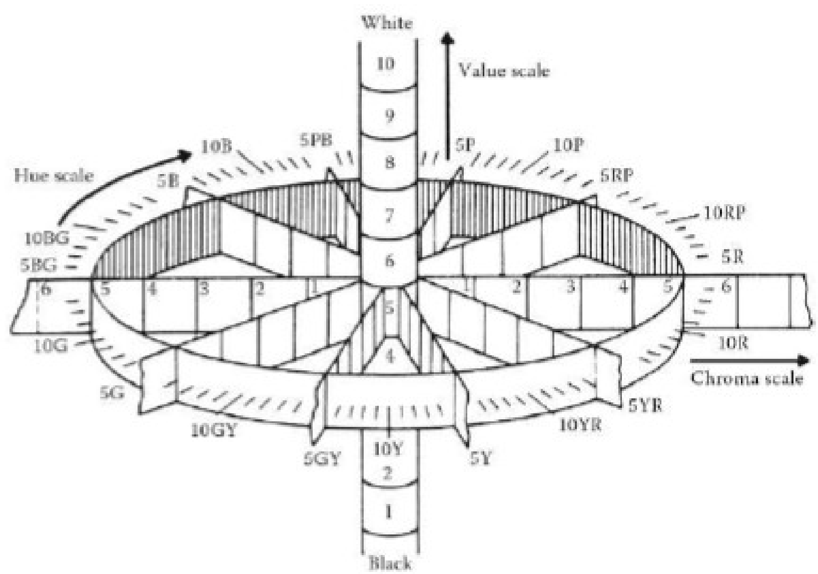

Figure 16: Organization of Munsell color order system (Boyce, 2014)

(Source: Boyce P. R (2014). *Human Factors in Lighting*.n. p. Boca Raton: CRC Press, Taylor & Francis Group, 2014)

2.5. Color and Visual task performance

Different visual tasks are performed in the workspace by the workers and color oriented tasks are in the category of difficult tasks. The interaction between a light source, an object and the human visual system lead to color perception of the objects (Egan, 1983). In the literature, different color and visual tasks such as color differentiation task, proof reading and typing tasks are used to investigate the human visual system and its interaction with the light source and the viewing object (Fisher, 1976; Shamsul et al., 2013; Lee , Moon & Kim, 2014). Color and visual task performances are measured according to speed and accuracy of performed tasks (Öztürk et al., 2012).

In the literature, there is information about the factors, which affect the color differentiation performance. For instance, the smaller the size of an object, the shorter time spent to discriminate and low illuminance level can decrease the differentiation ability for the visual system. For accurate color differentiations, the placement of the color samples should be done in a manner that the objects are adjacent not separated. Besides, luminance and contrast of the object with its immediate surrounding plays an important role in color task performances. Luminance or brightness is the amount of reflected light from an object. Luminance contrast values should be in the standard limits in order to reach high performance in color-oriented tasks. For instance, according to standards, there should be 3:1 luminance contrast between task and its darker surroundings (see figure 17) (Egan, 1983).

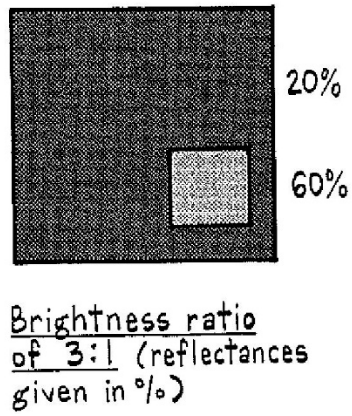

Figure 17: The luminance difference between an object and its darker surrounding.

(Source: Egan, M. D. (1983). *Concepts in architectural lighting*. New York: McGraw- Hill, c1983.)

Additionally, there are physical regulations and standards to be considered while performing color tasks. For instance while performing color task on a flat working surface, viewing angle of the observer should be 25 to 40 degrees (see figure 18).

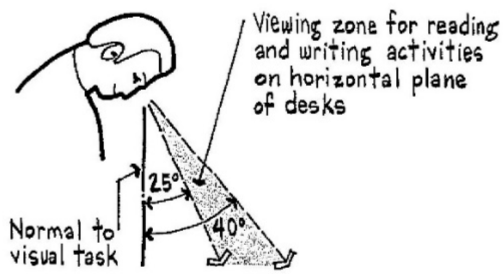

Figure 18: Viewing angle of an observer on flat working surface.

(Source: Egan, M. D. (1983). *Concepts in architectural lighting*. New York: McGraw- Hill, c1983.)

It is important to consider the viewing angle with the task surface to prevent veiling reflections. It is known that in flat work surfaces, the offending zone, which is the reflected glare cause by light source, covers a big area. However, inclined work surfaces lead to have smaller offending zone and closer to the observers, and correspondingly reduce veiling reflections. According to standards, it is better to use inclined working surfaces in workspaces.

The experiments showed that observers are not able to discriminate color attributes in color differentiation task with 100% correct score. As mentioned earlier, the hue attribute of color varies according to spectrum. According to a study, there should be a large change in wavelength in order to detect a difference in hue of red colors but for most of the other colors, almost 2nm is enough for detecting the change in hue (Fisher, 1976).

An experimental study was conducted by Melgosa et al., (2000) in order to understand the perception of three color attributes according to Munsell color task (see figure 19). The results showed that chroma was the most difficult attribute to differentiate but value and hue were the most accurately distinguishable attributes. The error rates were higher on identification of yellow hue zones. They examined that large hue differences were needed for better color identification. Besides, only constant hues are easy to discriminate while the difference between hues is too small.

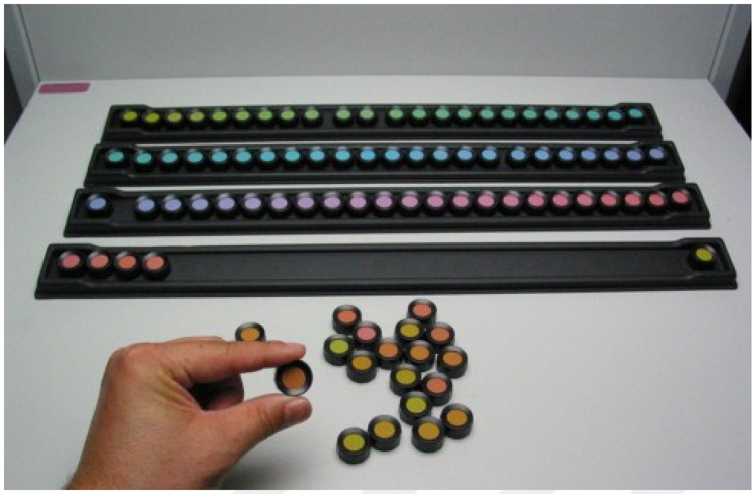

Figure 19: Farnworth-Munsel 100 hue test

(Source: http://www.visio-rx.com/vision-topics/eye-exams/testing-for-color-blindness)

In another study which investigated the color differentiation efficiency of different LED light sources, desaturated Lanthony-Panel D15 (DD15) color task performance test was used (Viénot et al., 2005). The Desaturated Panel D-15 consists of 16 caps, which its hues are the same as Munsell hues but the chroma and value are 2 and 8 from Munsell color order system respectively. It was used to examine the observers who have serious chromatic discrimination deficiency from observers with no color vision deficiencies (Lanthony, 1978).

Another experiment was conducted to observe the color discrimination efficiency of different LED light sources with a desaturated panel-like discrimination test. A discrimination test different from DD15 discrimination test was designed to use because DD15 has small intervals along yellow axis and not constant intervals along the CIELAB color space. The test was designed by Mahler et al., (2009) and consisted of 32 caps equally distributed along a color circle in CIELAB color space. CIELAB is an opponent color system adopted by CIE in 1976 (see figure 20) (Cie, 2004; Mahler et al., 2009).

Figure 20: Color discrimination test designed by Mahler et al., 2009

(Source: Mahler, E., Ezrati, J. J., & Viénot, F. (2009). Testing LED lighting for colour discrimination and colour rendering. *Color Research and Application*, *34*(1), 8–17.)

Lee et al., (2014) conducted a research to investigate the effects of color temperatures and illuminance levels of light sources on participants' visual perception and mood. They used computer and paper based visual tasks. For both of the visual tasks participants were asked to find the letters 'eul' and 'reul' in the given articles. The results of computer and paper based test performances showed that 3000K CCT and 750-lux illuminance level are not the proper CCT for office spaces.

The study conducted by Shamsul et al., (2013) states that accuracy of computer based acuity task is better under daylight compared to cool white light source. They investigated the effects of light sources with different CCTs on performance of participants in visual acuity and contrast test with 'Freiburg Visual Acuity and Contrast Test' (FrACT) in computer and paper based. The procedure of the experiment was same as the study conducted by Linhart & Scartezzini, (2011). At computer-based task, participants were asked to recognize the directions of Landolt rings as quick as possible with direction keys on the keyboard. Besides, for testing contrast threshold, there is contrast in the color of the Landolt rings and their background (see figure 21).

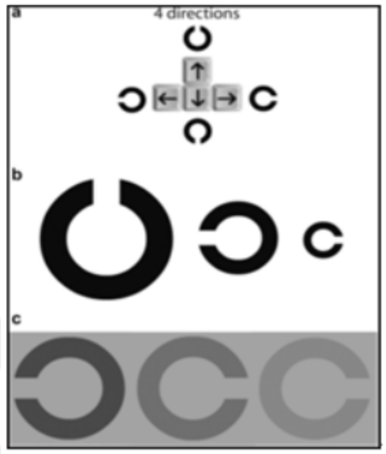

Figure 21: Computer based Freiburg Visual Acuity and Contrast Test: a) four directions of keyboard to be used during task. b) Visual acuity test. c) The contrast test

(Source: Shamsul, B. M. ., Sia, C. C., Ng, Y. ., & Karmegan, K. (2013). Effects of Light's Colour Temperatures on Visual Comfort Level, Task Performances, and Alertness among Students. *American Journal of Public Health Research*)

At paper-based task, 96 Landolt rings are printed in grey paper and participants are asked to find the number of Landolt ring for each direction from 96 rings (see figure 22).

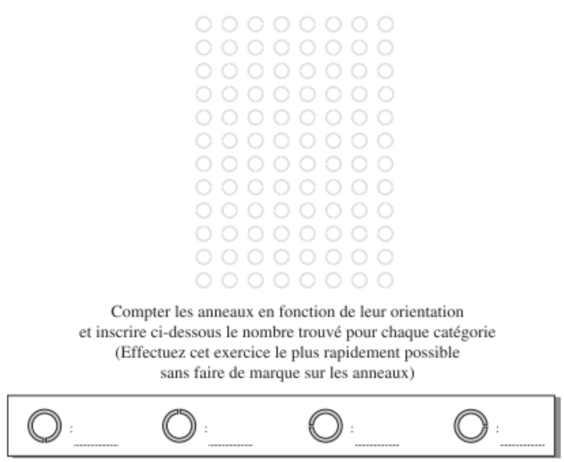

Figure 22: Paper based Freiburg Visual Acuity and Contrast Test
(Source: Linhart, F., & Scartezzini, J. L. (2011). Evening office lighting - visual comfort vs. energy efficiency vs. performance? *Building and Environment*, *46*(5), 981–989.)

CHAPTER III

This chapter presents the methodology of the thesis. The part on the design of the study covers the information about aims of the study, independent and dependent variables. Then research questions and hypotheses are explained. The method of the study section presents the experimental set up, technical specifications of light sources, color differentiation model test, questionnaire, sample group, process and phases of the experiment.

METHODOLOGY

3.1. Design of the study

This study aims to investigate the effects of spectral power distribution (SPD) characteristics of light sources on hue differentiation performance of participants in terms of accuracy and speed. The study also aims to investigate the effects of SPD characteristics on alertness level and perceived performance of participants. The cause and effect relationships are evaluated with the help of experimental design approach. In this experimental study, there are three systematically changing independent variables and two dependent variables. Independent variables are the light sources; Light Emitting Diode (LED), Compact Fluorescent light (CFL) and daylight simulator (D65). Dependent variables are the accuracy and speed of performing hue differentiation task, the analyses of which is the purpose of this study. CCTs of 4000K (natural white) and 6500K (cool white) CCTs were used in this study. LED and CFL are light sources with line SPD characteristics while D65 has continuous SPD characteristic.

Hue differentiation task designed by Kürkçü, (2017) is used in this study to investigate the effect of SPD characteristics on hue differentiation performance of participants. Participants performed the hue differentiation task voluntarily at a scheduled time. Besides, for evaluating the biological effects of SPD characteristics on participants a questionnaire is designed. The questionnaire of the study consists of perceived performance test and Karolinska Sleepiness Scale (KSS) test. Investigating the effects of SPD characteristics on hue differentiation performance of users can be helpful to improve lighting design technologies for workspaces, which would enhance better work performance and the well-being office workers.

3.1.1. Research Questions and Hypotheses

The main research questions of the study are as follow:

Q1: Is there any significant difference in terms of *accuracy* and *speed* in performing hue differentiation task under light sources with different spectral power distribution (SPD) characteristics?

Q1a: Are the hue differentiation chips sensitive to SPD characteristics of the light sources?

Q1b: Is there any significant difference in the alertness level of the participants after being exposed to the experiment under light sources with different SPD characteristics?

Q1c: Is there any significance difference in perceived performance of the participants after being exposed to the experiment under light sources with different SPD characteristics?

The hypotheses of the study are as follow:

H1: The *accurac*y and *speed* of performing hue differentiation task are significantly higher under D65 light source than LED and CFL it can be due to wide and continuous spectral power distribution (SPD) characteristic.

H1a: The hue differentiation chips are sensitive to SPD characteristics of the light sources.

H1b: There is significant difference in the alertness level of the participants after being exposed to the experiment under light sources with different SPD characteristics.

H1c: There is significance difference in perceived performance of the participants after being exposed to the experiment under light sources with different SPD characteristics.

3.2. Method of the study

Method of the study presents information about experimental set up, technical specifications of light sources, color differentiation model test, questionnaire, sample group, process and phases of the experiment. In the experimental set up section, the light booth and its placement in the lighting laboratory are described. In the next section, technical specifications of light sources such as their CCTs and SPD graphs are described. In the color differentiation section, the determined hue differentiation task is explained. The questionnaire part consists of the perceived performance questions and KSS question. Then the demographic information of sample group that participated in the study is explained. In the process of the experiment part, the process of participation in the experimental study is explained. The last part covers the phases of the experiment that consist of five main parts; Ishihara color blindness test, KSS test before the hue differentiation task, hue differentiation task, KSS after the hue differentiation task and perceived performance test.

3.2.1. Experimental set up

The study was performed inside a light booth that is in the lighting laboratory room of the Department of Interior Architecture and Environmental Design at Bilkent University. The dimension of the room is 4.10m to 4.18m with the height of 3.85m to the ceiling. The ceiling and walls of the room are painted in matte white (NCS-S 0300N). The floor of the laboratory is covered with 30*30 cm gray tiles. The room is a laboratory without any windows to exclude daylight and control the environmental effects. The placement of the light booth is in the right down corner of the room. There are also cabinets in the room, which are used as storage for light measurement equipment (see figure 23 and 24 and Appendix figure B2)

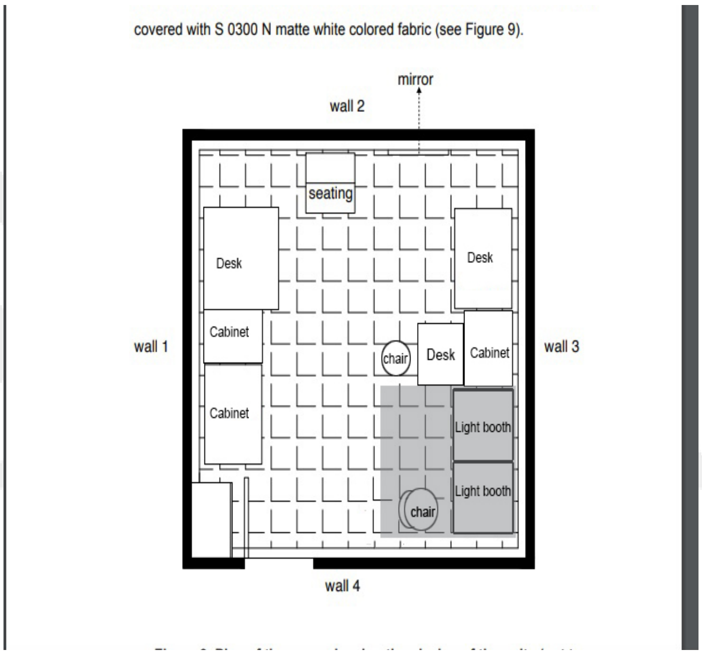

Figure 23: Plan of the experimental set up and placement of the light booth (not to scale)

Figure 24: Placement of the light booth in the experimental room

Light booth is a device that can simulate lighting conditions. It is the proper apparatus for testing products under a variety of lighting conditions independent of environmental influences. The user can accurately perform color tasks under a variety of conditions inside the light booth. Light booths are primarily used in the painting industry to test the finish color of products under controlled conditions. The light booth that is used in this study has 0.75m height, 0.5m length and 0.5m depth. The inner and outer surface of the light booth are coated with black paint (NCS-S9000N), maintaining the surface reflectance at zero percent to prevent the effects of surrounding colors.

Other equipment of the experimental set up should be prepared according to the ergonomics of the workspace in order to prevent any discomfort for the participants while doing the hue differentiation task. Consequently, an adjustable chair was prepared and placed in front of the light booth. The backrest and seat part of the chair were adjustable. Every participant could adjust the seat part of the chair for adjusting the eye level according to his/her comfortability. The eye level height was adjusted in between the range of 130-150 cm with regard to the participants' height. The distance between differentiation task surface and the participant was 20cm. The hue differentiation task was placed with 40 degree tilted task surface. This is because the position of the participants to the task can affect the reflections of surfaces, which may lead to veiling reflection and discomfort (Egan, 1983; CIBSE, 1984). Besides, the setup was designed in a way that participants organized 40-degree sitting line of sight and 60-degree cone of vision for preventing glare (IESNA, 1993) (see figure 25).

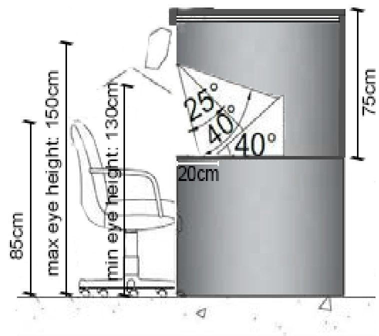

Figure 25: Section of the light booth set up (not to scale)

During the experiment, the general lighting of the room was turned off so that the participants were not affected by the surrounding environment and they could concentrate on the hue differentiation task in the light booth (see figure 26).

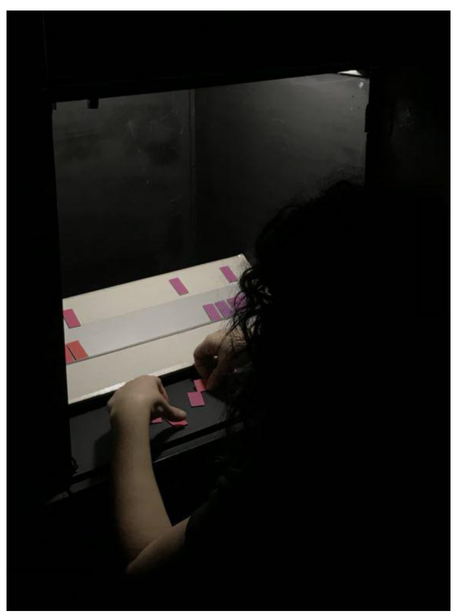

Figure 26: Hue differentiation task inside the light booth while the general lighting was turned off.

3.2.2. Technical specification of light sources

Light Emitting Diode (LED), Compact Fluorescent light (CFL) and simulator of daylight (D65) were used as light sources in this study. One OSRAM LED star Cla 9,5W/4000K (natural white), one OSRAM compact fluorescent 20W/4000K (natural white) and one D65 Philips TLD 18w/6500K (cool daylight) were used. In this study, 4000K (cool white) as according to literature it is the most proper CCT for color task performances and 6500K (cool daylight) due to its wide and continuous band spectra, CCTs were used. According to CIBSE, high color rendering index (CRI) values of light sources is needed for performing color-oriented task accurately (1984). According to IESNA, proper range of CRI value for performing color-oriented tasks is 80-90 Ra (1993). All of the light sources in this study had CRI of ≥80 that were measured by their manufactured company (see table 3). The lamps were placed in the middle top of the light booth during the experiment.

Table 3: Technical specifications of light sources.

	Picture	Brand	CCT	Illuminance Level	CRI	Wattage	Lumen
LED		OSRAM	4000K	610lux	>80	9,5 W	806
CFL		OSRAM	4000K	600lux	>80	20W	1300
D65		PHILIPS	6500K	590lux	>80	18W	1055

The illuminance meter Konica Minolta T-1 Illuminance Meter (range of 0.01 to 99,900 lux) on working surface was used for measuring the illuminance levels. The measurements were applied at one point below the center of the light sources by replacing the illuminance meter at the center of the working surface while the general lighting of the room was turned off (see figure 27). The acquired illuminance levels were approximately the same for the light sources; for LED lighting 610lux, for CFL 600lux and for D65 590lux.

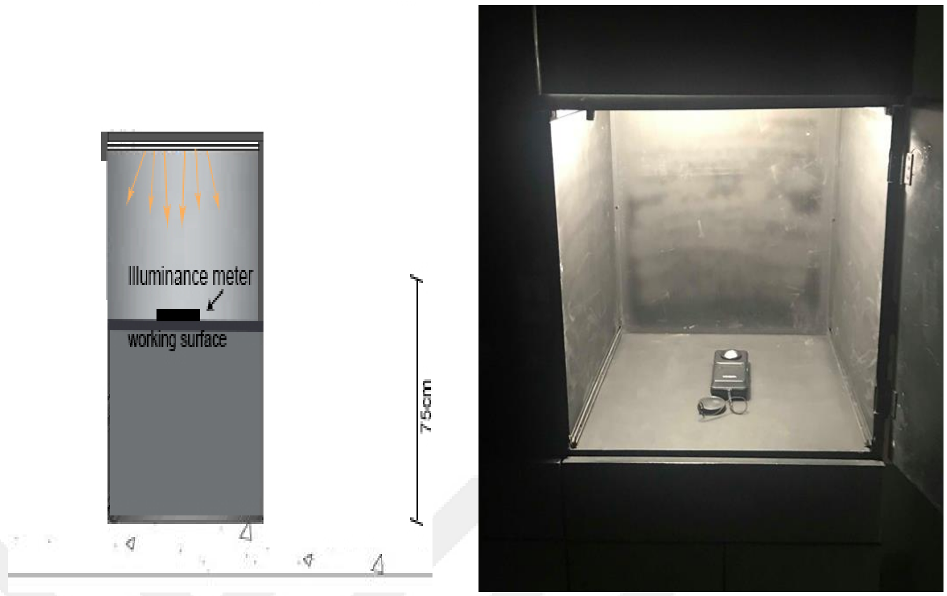

Figure 27: Measurement with illuminance meter on the working surface.

The Spectral Power Distribution (SPD) of CFL and LED light source were measured with a calibrated optical spectrum analyzer Thorlab compact CCD spectrometer version 2.0.507.1175. This version of compact CCD spectrometers is for wavelength ranges of 500-1000 nm. This spectrometer is with graphical user interface which means it is acquired the SPD of the light source, the background and peaks in a single graph. This device has a peak track mode for analyzing. It tracks the position, amplitude and width of peaks in the spectrum over time. The measurement was performed through the cable of the spectrum, holding the cable on the light bulb tightly leads to acquiring the SPD graph in the monitor connected to the device (Thorlabs, 2014) (see figure 28 and 29). LED and CFL light sources have line SPD characteristics as can be seen in their SPD graph figure. However, D65 has a continuous SPD characteristic and its SPD was acquired from its manufacturer company.

Figure 28: Spectrum analyzer Thorlab Compact CCD

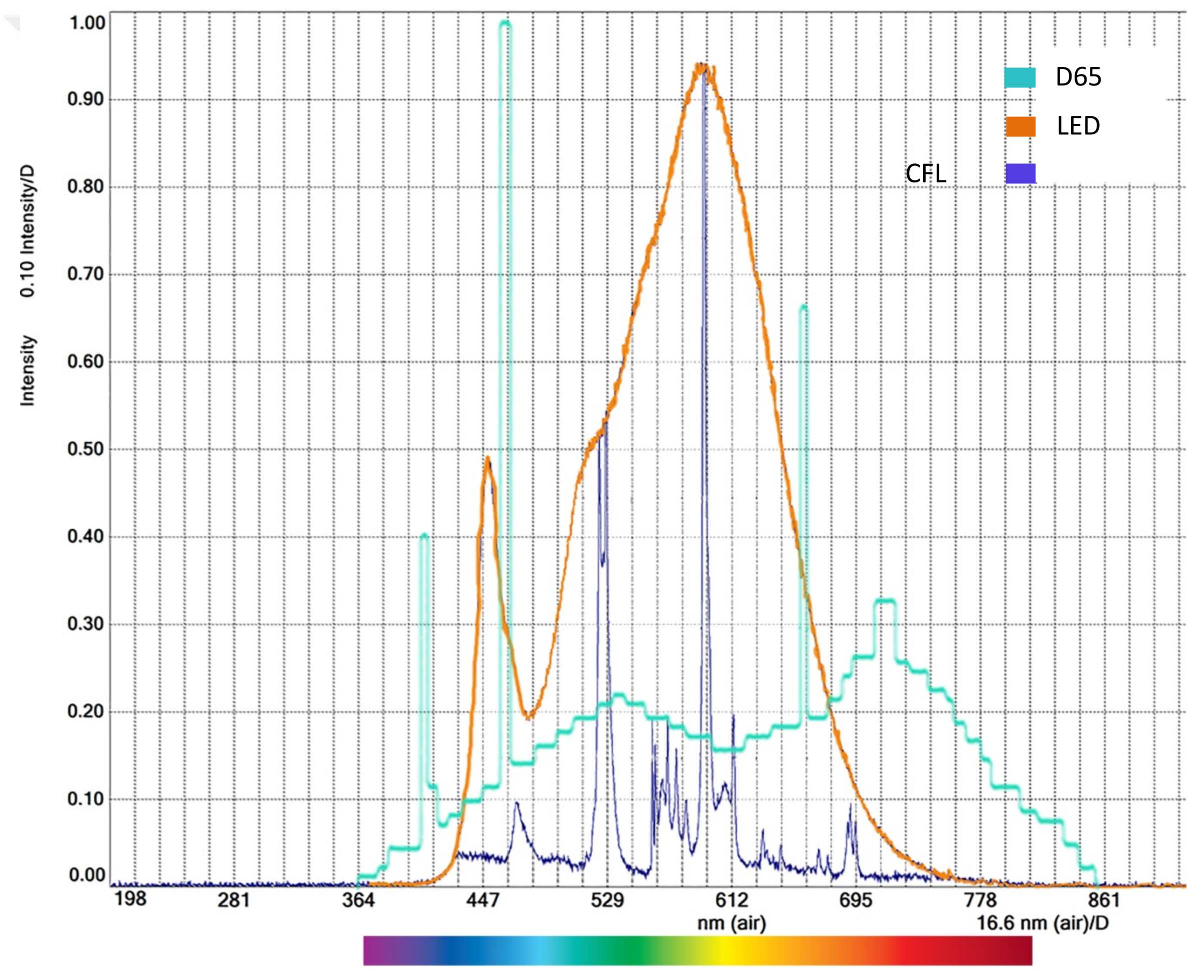

Figure 29: Spectral power distribution graph of the light sources.

3.2.3. Color differentiation model test

In this study hue attribute of color was used in order to investigate the effects of SPD characteristics of different light sources on differentiation performance of the participants. The experiment tool was a two dimensional color differentiation task model from Kürkçü's previous study (2017). Color differentiation task model explained by Kürkçü (2017) (see figure 30, 31, 32, 33 and 34):

> Since colors are perceived, depending upon the recognition of three attributes which are hue (name of the color), value (lightness of color) and chroma (degree of strength of color), the color tasks were designed in order to assess how three attributes of colors are differentiated. The color tasks were prepared by using Munsell system since the participants received their basic design education based on Munsell System. Three types of color task (hue differentiation, chroma differentiation, value differentiation) were designed with Adobe Photoshop CS6, printed out high quality (600 dpi) by HP DESIGNJET Z6200 Photo Production Printer on matte paper and cut into 20 pieces with the dimensions of 2cm (length) to 4cm (height). The size of the chips was determined based on previous research which was studied unique hue selection and used color chips 2x4 cm (Shamey, 2015). In order to find out in which range color differentiation is more sensitive, each chip differs one and other 5% levels.
>
> In the Munsell color system, there are five Principal Hues (red, yellow, green,blue and purple) which are visually equidistant from each other. These hues divide the hue circle into five equals distance. Each principal hue has 20 steps distant to the other principal hue (Cooper, 1941). To assess hue differences, five principal hues and their evenly-graded alteration from one hue to another were used. Hue differentiation task contains five sets; red to yellow, yellow to green, green to blue, blue to purple and purple to red. Tasks assess color differentiation performance on all of the hues in the 100-hue circuit and hue differentiation sensitivity.

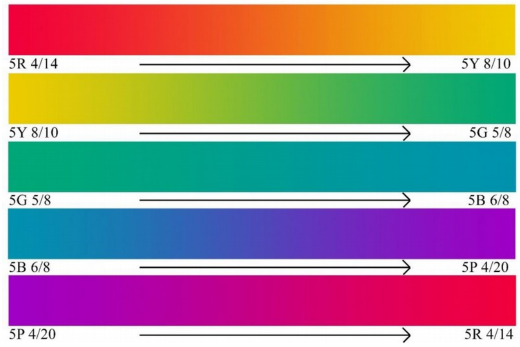

Figure 30: Hue differentiation task

(Source: Kurkcu, E., (2017). *The effects of color temperature on performance and mood of users: a color task implementation model.* (Master thesis, Bilkent Univeristy, Ankara, Turkey). Retrieved from: http://repository.bilkent.edu.tr/handle/11693/33499)

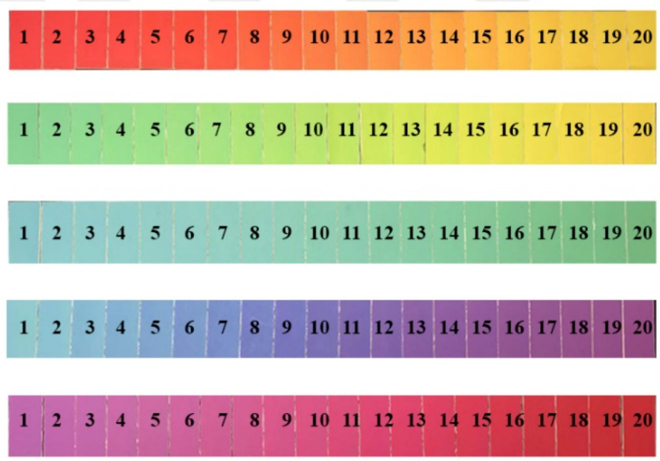

Figure 31: Chips of hue differentiation task

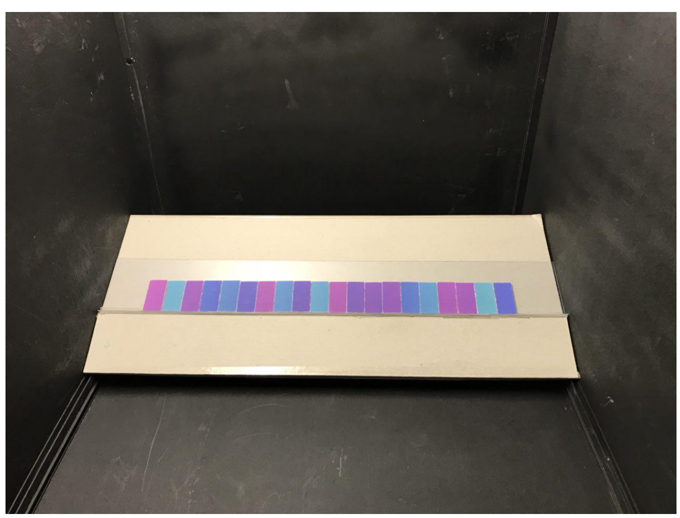

Figure 32: An example of random arrangement of hue differentiation task inside the light booth (blue to purple hue task)

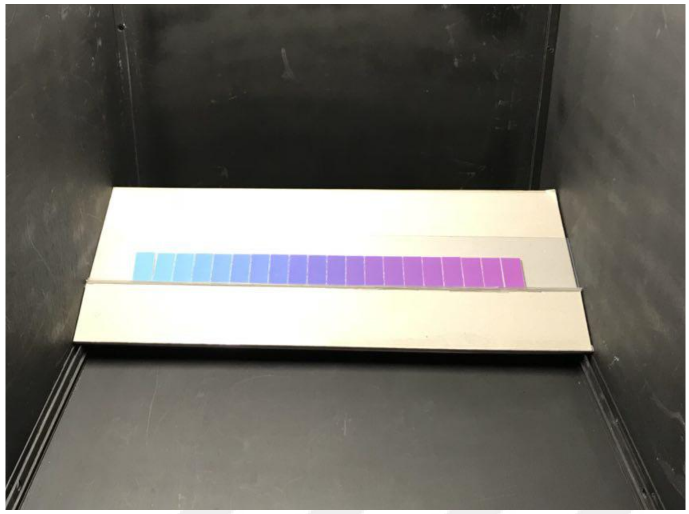

Figure 33: An example of accurate arrangement of blue to purple hue differentiation task inside the light booth

Figure 34: An example hue differentiation chips performed by a participant (process of checking the arrangement)

3.2.4. Questionnaire

The questionnaire of the study was designed to investigate subjective alertness level and perceived performance because SPD of light sources and the illuminated hue differentiation task can have non-visual biological effects on participants. The questionnaire consists of three subjective self-report questions; Karolinska Sleepiness Scale (KSS) test before and after the experiment, and the other part consists of subjective evaluation of perceived performance.

Participants were asked to evaluate their alertness level according to Karolisnka Sleepiness Scale (KSS) before and after the experiment. KSS is a scale for evaluating the situational subjective sleepiness level at a particular time during the day. This scale is acquired by asking the participants to express their level of psychophysical state in the last ten minutes. It consists of nine scales; being "extremely alert" (1) to "very sleepy, a great effort to keep awake" (9) (see figure 35) (Shahid et al., 2012; Åkerstedt et al., 2014).

1	Extremely alert
2	Very alert
3	Alert
4	Rather alert
5	Neither alert nor sleepy
6	Some signs of sleepiness
7	Sleepy, but no effort to keep awake
8	Sleepy, some effort to keep awake
9	Very sleepy, great effort to keep awake, fighting sleep

Figure 35: Karolinska Sleepiness Scale (KSS)

(Source: Åkerstedt, T., Anund, A., Axelsson, J., & Kecklund, G. (2014). Subjective sleepiness is a sensitive indicator of insufficient sleep and impaired waking function. *Journal of Sleep Research*, *23*(3), 240–252.)

Another part of the questionnaire was conducted to evaluate the perceived performance of the participants under each light source in a subjective self-report manner. Participants evaluated their own performance on a 5-point Likert scale. The test consists of three questions; evaluating the overall success, their attention to speed and their attention to accuracy after exposed to the experiment (see figure 36).

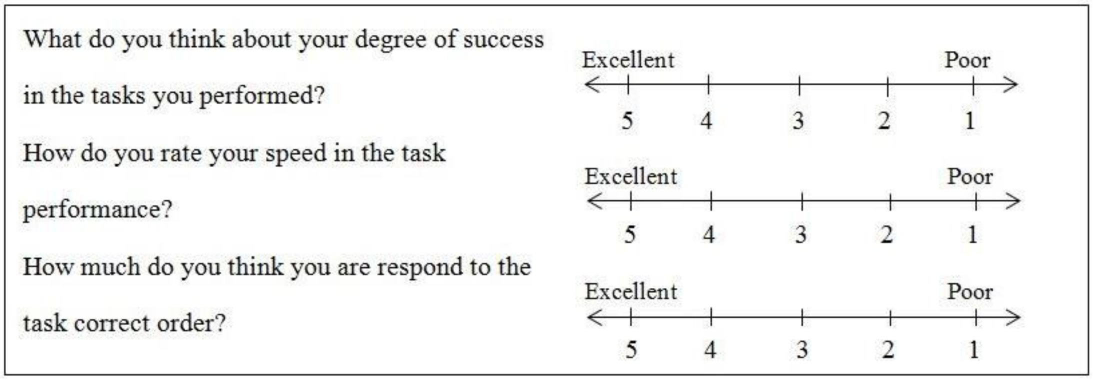

Figure 36: Perceived performance test

3.2.5. Sample group

The participants were students from Bilkent University and Middle East Technical University, Ankara, Turkey. Ninety students, which consist of 51 females and 39 males, performed the hue differentiation task voluntarily. The students were from different departments of these two universities. The mean age of the participants was 24 ranging from 19 to 31 years. Effect of age and gender did not examined as independent variables in this study. They participated in the experiment in fall semester 2017.

3.2.6. Process of the experiment

The participants were examined in this survey with between subjects design method. Between subjects design methods, means that each participant performed the hue differentiation task under just one light source and at one time. Ninety participants were divided randomly into three. Each group of thirty participants performed the hue differentiation task under different light source and for just one time as long as controlling the influences of extraneous variables and practice effects (see table 4). This is because even if the color tasks were given randomly by performing the same hue task performance under three of the light situations and for three times will lead to higher speed and accuracy in the second and third situation due to the practice effect (Shaughnessy et al.,2012).

Table 4: Process table of the experiment

	Red to yellow	**Green to yellow**	**Blue to green**	**Purple to blue**	**Red to purple**
LED	S1…S30 ↔	S1…S30 ↔	S1…S30 ↔	S1…S30 ↔	S1…S30
	↕	↕	↕	↕	↕
CFL	S31…S60 ↔	S31…S60 ↔	S31…S60 ↔	S31…S60 ↔	S31…S60
	↕	↕	↕	↕	↕
D65	S61…S90 ↔	S61…S90 ↔	S61…S90 ↔	S61…S90 ↔	S61…S90

3.2.7. Phases of the experiment

The experiment consists of five main phases; Ishihara color blindness test, alertness level before the experiment, hue differentiation task, alertness level after the experiment and subjective report of perceived performance (see figure 37).

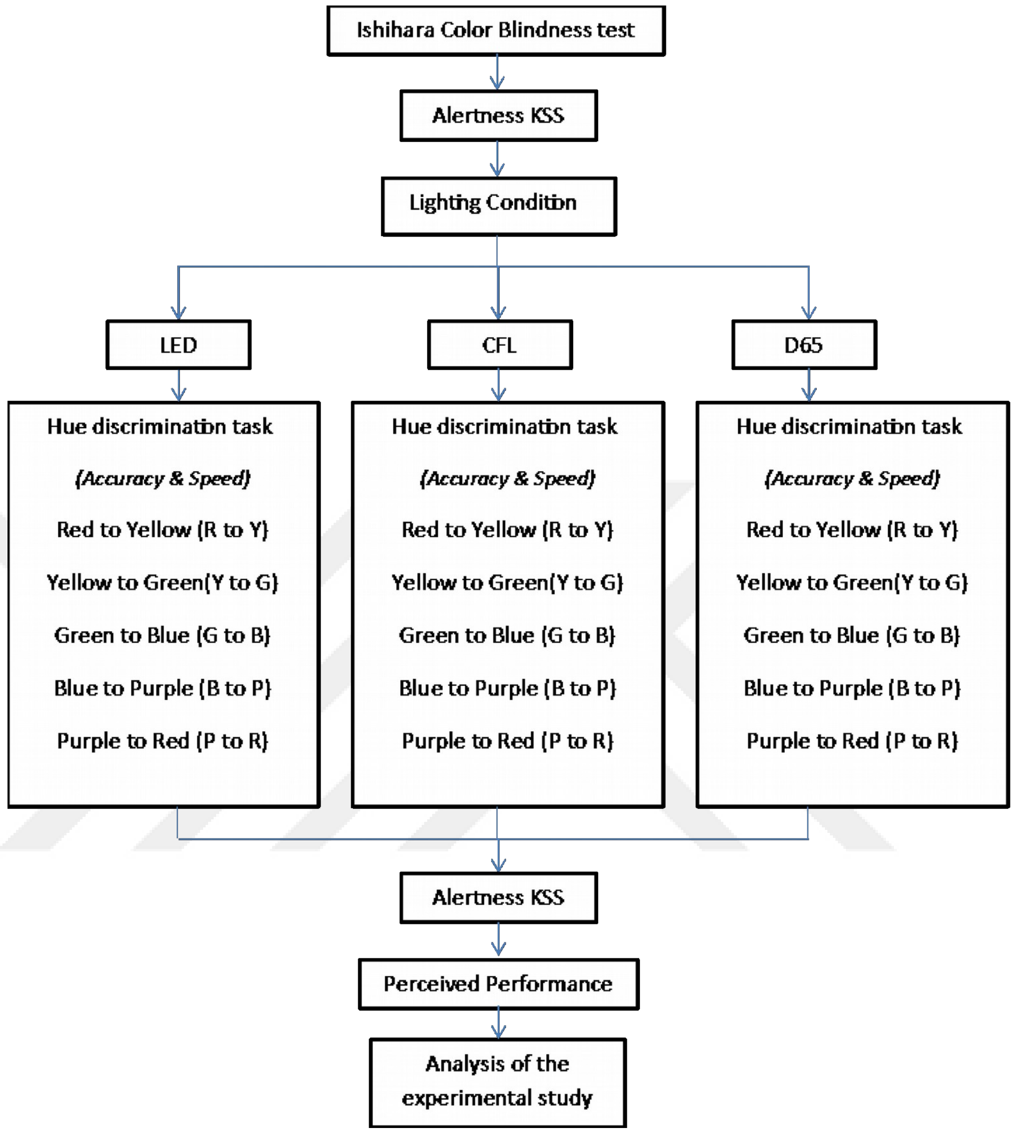

Figure 37: Phases of the experiment

The participants entered the experiment room one by one on the scheduled time and day. The general lighting of the room and the light source inside the light booth were turned on fifteen minutes before the entrance of the participant. In the first phase of the experiment, participants were tested for color vision with Ishihara color blindness test. Then they evaluated their alertness scale before starting the experiment with KSS questionnaire. Then the general downward lighting of the room was turned off and almost

10 minutes was given to the participant for adaptation to the lighting inside the light booth (Manav et al., 2013). After the adaptation to the light exposure, the hue differentiation task was explained to the participant. At this stage, information was given only on how to perform the hue differentiation task.

Participant was asked to start performing the hue differentiation task. The time of doing each hue differentiation task was recorded. The order of performing the hue differentiation task was given randomly to the participant. One participant may start with performing red to yellow hue differentiation task and the other with green to blue hue differentiation task. A mobile phone application in IOS version with the name of 'Random' was used for randomizing the order of hue differentiation task performed by the participant. The whole experiment took approximately 25 minutes with each of the participants.

After finishing the hue differentiation task, general lighting of the room was turned on and the participant was asked to answer to the second question of the questionnaire that was about evaluating his/her own performance in hue differentiation task. The participants evaluated their own performance under three sections; their own success, attention to speed and attention to accuracy. Lastly, they evaluated their alertness scale after the experiment.

CHAPTER IV

This chapter presents the data analyses, results of the experimental study and discussion part of the thesis. In the data analyses part, the statistical tests used for analyzing the differences between and within groups are described. Then the results of the statistical analyses are covered under five sections; the effects of SPD characteristics on the hue differentiation performance in terms of accuracy & in terms of speed; hue differentiation sensitivity of each chip; effects of SPD characteristics on alertness level and perceived performance. In the discussion part of this chapter the relation between the results of this study and the results of the previous studies are discussed.

RESULTS AND DISCUSSION

4.1. Data analyses

Data of the study were analyzed using Statistical Package for the Social Sciences (SPSS) version 24.0. Statistical tests were chosen and analyzed according to hypotheses of the study (see hypotheses in the section 3.1.1). Different statistical tests were used for analyzing the differences between and within groups. Firstly, Shapiro Wilk-W test which is a test that shows whether the data are normally distributed or not was used to understand whether parametric or non-parametric test is the proper test to follow up the study of the differences between and within groups. The results of Shapiro Wilk-W test showed that P values were all smaller than 0.05 so it was observed that the data were not normally distributed in this study. Consequently, non-parametric tests were chosen for analyzing the differences between and within groups.

In order to evaluate the differences in hue differentiation performance under light sources with different SPDs Kruskal-Wallis H Rank was used. It is a rank based non-parametric test that was used for two or more groups of an independent variable on a continuous or ordinal dependent variable. However, for investigating the difference between two independent groups Mann-Whitney U test is the proper test to be used. Besides the Kruskal-Wallis H, Post hoc test was used for evaluating the pairwise comparison of difference between independent groups.

Repeated-Measures ANOVA test was used for understanding the differences within subject groups. Repeated-Measures ANOVA is the extension of the dependent t-test and is used for related subjects. It is the test to be used while the same sample unit's performance, behavioral and psychological measurement changes over time under different conditions (Thomas & Zumbo, 2012).

The Spearman's rank-order correlation test as a nonparametric test was used for evaluating the correlation between speed and accuracy. It is the non-parametric version of the Pearson product-moment correlation. Spearman's correlation coefficient, (ρ, also signified by r_s) evaluates the direction of correlation between two ranked base dependent variables. It is also used to observe and evaluate whether there is monotonic relationship between two variables or not. Monotonic relationship stands for the cases when values of both variables increase or decrease together.

4.2. Results

Results of the statistical tests are explained under five sections; results of the statistical tests for analyzing the effects of SPD characteristics of different light sources on the hue differentiation performance in terms of accuracy, in terms of speed, hue differentiation sensitivity of chips, the effects of SPD characteristics on alertness level and on perceived performance.

4.2.1. The effects of SPD characteristics on the hue differentiation performance in terms of accuracy

The effects of SPD characteristics of three different light sources on hue differentiation performance in terms of accuracy were analyzed under three sections to investigate the differences between and within groups; total differentiation performance irrespective of the hues under different light sources, hue differentiation performance under different light sources and hue differentiation performance within each light source group.

Firstly, the difference in total differentiation performance *irrespective of the hues* in terms of accuracy between light sources with different SPD characteristics was examined. The results of Kruskal-Wallis H Rank test showed that there was a significant difference of accuracy in arranging chips under different light sources (Chi-square=12.54, p=0.002) (see table 5). The mean accuracy values showed that participants made highest accurate arrangements of total color chips irrespective of the hues under D65 followed by CFL and LED (see table 5).

Table 5: Results of Kruskal-Wallis H rank test for differences in accuracy between light sources.

	LED		**CFL**		**D65**		**LED / CFL / D65** *(Kruskal-Wallis H)*	
	Mean	Std.	Mean	Std.	Mean	Std.	Chi-square	P
Total Accuracy *(no. of correct arrangements)*	18.25	2.023	18.45	2.116	19.05	1.402	12.540	**0.002

**The significance level was 0.05.

Man-Whitney U test was performed to find out that the difference occurred between which two light sources. The results showed that the significant differences in accuracy of performing differentiation tasks were between LED and D65 light sources (z=-3.567, p=0.005) and between CFL and D65 light sources (z=-2.133, p=0.033) (see table 6). Under D65, number of correct arrangements of color chips was higher compared to LED light source and CFL.

Table 6: Results of Man-Whitney U rank test for differences in accuracy between each two light sources.

(Man-Whitney U test)	**LED / D65**		**CFL / D65**		**CFL / LED**	
	Z	P	Z	P	Z	P
Total Accuracy *(no. of correct arrangements)*	-3.567	**0.00	-2.133	*0.033	-1.305	0.192

**The significance level was 0.05.

Secondly, the differences in *hue* differentiation performance in terms of accuracy between light sources with different SPD characteristics were examined. The results of Kruskal-Wallis H Rank test indicated that there was a significant difference in accuracy of arranging red to yellow (R to Y) (Chi-square=6.667, p=0.036) and green to blue (G to B) hue differentiation task (Chi-square=15.08, p=0.001) between light sources (see table 7). The number of correct arrangements of (R to Y) hue differentiation chips was highest under D65 followed by LED and CFL. In arranging (G to B) hue differentiation chips, participants made the highest accurate arrangements under D65 followed by CFL and LED (see table 7).

Despite the fact that the accuracy of performing yellow to green (Y to G) (Chi-square=1.488, p=0.475), blue to purple (B to P) (Chi-square=0.287, p=0.866), and purple to red (P to R) (Chi-square=1.267, p=0.531) hue differentiation tasks were highest under D65 followed by CFL and LED, the differences were not statistically significant (see table 7).

Table 7: Results of Kruskal-Wallis H rank test for differences in accuracy of performing hue differentiation between light sources.

Accuracy *(no. of correct answers)*	LED		CFL		D65		Kruskal-Wallis H	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Chi-square**	**p**
Red-Yellow Hue	17.80	1.846	16.97	2.593	18.60	1.453	6.667	*0.036
Yellow-Green Hue	18.73	2.116	19.20	1.448	19.30	1.264	1.488	0.475
Green-Blue Hue	17.17	2.350	18.13	2.063	19.33	1.213	15.08	**0.001
Blue – Purple Hue	18.97	1.497	19.03	1.974	19.07	1.337	0.287	0.866
Purple-Red Hue	18.57	1.755	18.93	1.574	18.93	1.660	1.267	0.531

**The significance level was 0.05.

Post hoc pairwise comparison was performed to find out that the significant difference in accuracy of arranging red to yellow (R to Y) occurred between which two light sources. Besides, to find out the difference in accuracy of arranging green to blue (G to B) hue differentiation task occurred between which two light sources. The results showed that the accuracy of arranging (R to Y) hue chips was significantly different between D65 and CFL (Z=-16.65, p=0.03) (see table 8). Participants made significantly higher accurate arrangements of (R to Y) hue chips under D65 compared to CFL. The results also showed that the accuracy of arranging (G to B) hue chips was significantly different under LED and D65 light sources (Z=-24.133, p=0.00) (see table 8). Participants made significantly higher accurate arrangements of (G to B) hue chips under D65 compared to LED.

Table 8 : Pairwise comparison of (R to Y) and (B to G) hue differentiation performance in terms of accuracy

Accuracy *(Post hoc pairwise)*	**LED / D65**		**CFL / D65**		**CFL / LED**	
	Z	P	Z	P	Z	P
Red to Yellow	-9.6	0.414	-16.65	**0.03	7.05	0.828
Blue to Green	-24.133	**0.00	-13.967	0.076	-10.167	0.31

**The significance level was 0.05.

Thirdly, the analysis of differences in accuracy of arranging hue chips within each light source was examined. The results of Repeated-Measures ANOVA showed that the accuracy of arranging different hue chips was significantly different under LED and CFL light sources (F=5.526, p=0.005), (F=8.813, p=0.0005) respectively (see table 9). Under LED light source, participants made the most accurate arrangements on blue to purple (B to P) and the most incorrect arrangements on green to blue (G to B) hue chips. Under CFL, participants made the most accurate arrangements on yellow to green (Y to G) and the most wrong arrangements on red to yellow (R to Y) hue chips (see table 9).

Table 9 : Results of repeated measures ANOVA for differences in accuracy between hue differentiation tasks.

Accuracy	Red-Yellow Hue		Yellow-Green Hue		Green-Blue Hue		Blue – Purple Hue		Purple-Red Hue		Repeated Measures ANOVA	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**F**	**p**
LED	17.8	1.84	18.73	2.11	17.17	2.35	18.97	1.497	18.57	1.755	5.526	*0.00
CFL	16.97	2.59	19.2	1.44	18.13	2.06	19.03	1.974	18.93	1.574	8.813	**0.0005
D65	18.6	1.45	19.3	1.26	19.33	1.21	19.07	1.33	18.93	1.66	1.838	0.15

**The significance level was 0.05.

Post hoc pairwise comparison was performed to find out that the significant differences in accuracy occurred between which two-hue differentiation tasks under CFL and LED light sources separately.

The results showed that under LED light source, the accuracy was significantly different between arrangements of yellow to green (Y to G) and green to blue (G to B) hue chips ($Z=1.567$, $p=0.018$) and between green to blue (G to B) and blue to purple (B to P) hue chips ($Z=-1.8$, $p=0.009$) (see table 10). Participants made lower accurate arrangements in (G to B) hue chips compared to both (Y to G) and (B to P) hue chips. The SPD characteristics of LED light source most affected the arrangement of (G to B) hue differentiation task.

Additionally post hoc pairwise comparison results showed that under CFL light source, the accuracy was significantly different between arrangements of (R to Y) and (Y to G), (B to P) and (P to R) hue chips ($Z=-2.23$, $p=0.0005$), ($Z=-2.06$, $p=0.002$), ($Z=-1.96$, $p=0.0005$) respectively (see table 10). Participants made less accurate arrangements in (R to Y) compared to (Y to G), (B to P) and (P to R) hue chips. The SPD characteristics of CFL most affected the arrangement of (R to Y) hue differentiation task.

Table 10: Pairwise comparison of accuracy between different hue tasks under LED and CFL

Accuracy *(Post-hoc Pairwise)*		**LED**		**CFL**	
		Z	**P**	**Z**	**P**
Red to yellow	Yellow to green	-0.933	0.251	-2.233	**0.00
	Green to blue	0.633	1	-1.167	0.481
	Blue to purple	-1.167	0.053	-2.067	**0.002
	Purple to red	-0.767	0.782	-1.967	**0.00
Yellow to green	Red to Yellow	0.933	0.251	2.233	0.00
	Green to blue	1.567	*0.018	1.067	0.168
	Blue to purple	-0.233	1	0.167	1
	Purple to red	0.167	1	0.267	1
Green to blue	Red to Yellow	-0.633	1	1.167	0.481
	Yellow to green	-1.567	0.018	-1.067	0.168
	Blue to purple	-1.8	**0.009	-0.9	0.831
	Purple to red	-1.4	0.081	-0.8	0.848
Blue to purple	Red to Yellow	1.167	0.053	2.067	0.002
	Yellow to green	0.233	1	-0.167	1
	Green to blue	1.8	0.009	0.9	0.831
	Purple to red	0.4	1	0.1	1
Purple to red	Red to Yellow	0.767	0.782	1.967	0.00
	Yellow to green	-0.167	1	-0.267	1
	Green to blue	1.4	0.081	0.8	0.848
	Blue to purple	-0.4	1	-0.1	1

**The significance level was 0.05.

4.2.2. The effects of SPD characteristics on the hue differentiation performance in terms of speed

The effects of SPD characteristics of three different light sources on hue differentiation performance in terms of speed were analyzed under three sections in order to investigate the differences between and within groups: total differentiation performance irrespective of the hues under different light sources, hue differentiation performance under different light sources, and hue differentiation performance within each light source group.

Firstly, the differences in total differentiation performance irrespective of the hues between light sources in terms of speed were examined. The results of Kruskal-Wallis H Rank test showed that there was a significant difference in terms of speed in performing differentiation tasks between different light sources (Chi-square=12.222, p=0.002) (see table 11). Under D65 light source, participants differentiated the colors with higher accuracy and faster speed, while under LED light source less accuracy and slower speed were observed.

Table 11: Results of Kruskal-Wallis H rank test for differences in speed between light sources.

	LED		**CFL**		**D65**		**LED / CFL / D65** *(Kruskal-Wallis H)*	
	Mean	Std.	Mean	Std.	Mean	Std.	Chi-square	P
Total Speed	100.09	24.924	104.58	32.665	110.73	29.392	12.222	**0.002

**The significance level was 0.05.

Man-Whitney U test was performed to find out the significant differences occurred between which two light sources. The results showed that the differences were between LED and D65 (z=-3.396, p=0.001) and between CFL and D65 (z=-2.543, p=0.011) (see table 12). Participants arranged the differentiation tasks with faster speed under D65 compared to CFL and LED light sources.

Table 12: Results of Man-Whitney U rank test for differences in speed between each two light sources.

(Man-Whitney U test)	**LED / D65**		**CFL / D65**		**CFL / LED**	
	Z	P	Z	P	Z	P
Total Speed	-3.396	**0.001	-2.543	*0.011	-0.584	0.559

**The significance level was 0.05.

Secondly, the differences in hue differentiation performance between different light sources were examined in terms of speed. The results of Kruskal-Wallis H Rank test showed that there was a significant difference in the speed of arranging yellow to green (Y to G) hue chips between different light sources (Chi-square=7.258, p=0.027) (see table 13). The speed of arranging the (Y to G) hue chip was fastest under D65 light source followed by CFL and LED light sources (see table 13).

Although the speed of arranging red to yellow (R to Y) (Chi-square=1.383, p=0.5) and green to blue (G to B) (Chi-square=2.557, p=0.278) was fastest under D65 light source followed by LED and CFL, the differences were not statistically significant. The speed differences in arranging blue to purple (B to P) (Chi-square=2.611, p=0.271) and purple to red (P to R) (Chi-square=1.504, p=0.472) were also observed. However, these differences were not statistically significant (see table 13).

Table 13: Results of Kruskal-Wallis H rank test for differences in speed of performing hue differentiation between light sources.

Speed	LED		CFL		D65		Kruskal-Wallis H	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Chi-square**	**p**
Red -Yellow hue	98.57	24.448	96.70	28.834	105.67	34.304	1.383	0.5
Yellow-Green hue	97.37	24.450	98.20	25.315	113.80	28.67	7.258	**0.027
Green-Blue hue	100.6	22.02	105.43	31.02	112.5	34.475	2.557	0.278
Blue- Purple hue	102.83	27.682	113.43	44.247	113.30	26.922	2.611	0.271
Purple-Red hue	101.1	26.94	109.13	26.668	108.40	21.874	1.504	0.472

**The significance level was 0.05.

Post hoc pairwise comparison was performed to find out the significant difference in speed of performing yellow to green (Y to G) hue chips occurred between which two light sources. The results showed that there was a significant difference in terms of speed in arranging (Y to G) hue chips between LED and D65 light sources (Z=-16.65, p=0.04) (see table 14). The speed of arranging (Y to G) hue chips was significantly faster under D65 compared to LED light source.

Table 14: Pairwise comparison of (R to Y) and (B to G) hue differentiation performance in terms of accuracy

SPEED *(Post hoc pairwise)*	**LED / D65**		**CFL / D65**		**CFL / LED**	
	Z	P	Z	P	Z	P
Yellow to Green	-16.65	*0.04	-14.6	0.091	-2.05	1

**The significance level was 0.05.

Thirdly, the differences in speed between hue differentiation tasks within each light source were examined. The results of Repeated Measures ANOVA showed that the speed of performing hue differentiation tasks was significantly different under CFL (F=2.996, p=0.037) (see table 15). The speed of arranging blue to purple (B to P) hue chips was fastest followed by purple to red (P to R), green to blue (G to B), yellow to green (Y to G) and red to yellow (R to Y) under CFL (see table 15).

Table 15: Results of repeated measures ANOVA for differences in speed between hue differentiation tasks.

Speed	Red-Yellow Hue		Yellow-Green Hue		Green-Blue Hue		Blue – Purple Hue		Purple-Red Hue		Repeated ANOVA	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**F**	**p**
LED	97.33	26.7	96.87	25.4	100.17	22.75	102.47	28.05	101.1	26.94	0.708	0.588
CFL	96.70	28.83	98.20	25.31	105.43	31.02	113.43	44.24	109.13	26.66	2.996	*0.037
D65	105.6	34.30	113.8	28.67	112.5	34.47	113.3	26.92	108.4	21.78	0.75	0.56

**The significance level was 0.05.

Post hoc pairwise comparison was performed to find out the performance of which two hue discrimination tasks in terms of speed were significantly different under CFL. The results showed that there were significant differences in terms of speed in the arrangement between red to yellow (R to Y) and blue to purple (B to P) hue chips (Z=-16.733, p=0.011) and between red to yellow (R to Y) and purple to red (P to R) hue tasks (Z=-12.433, p=0.017) (see table 16). The participants arranged the (R to Y) hue chips with lower speed compared to the speed of arranging both (B to P) and (P to R) hue chips. There was also significant difference in terms of speed in the arrangement of yellow to green (Y to G) and blue to purple (B to P) hue chips (Z=-15.233, p=0.048) (see table 16). Besides, there was significant difference in speed of arranging yellow to green (Y to G) and purple to red (P to R) hue chips (Z=-10.933, p=0.035). The participants arranged the (Y to G) hue chips with lower speed compared to the speed of arranging both (B to P) and (P to R) hue chips.

Table 16: Pairwise comparison of speed between different hue tasks under CFL

Speed *(Post-hoc Pairwise)*		**CFL**	
		Z	**P**
Red to yellow	Yellow to green	-1.5	0.657
	Green to blue	-8.733	0.065
	Blue to purple	-16.733	**0.011
	Purple to red	-12.433	**0.017
Yellow to green	Red to Yellow	1.5	0.657
	Green to blue	-7.23	0.183
	Blue to purple	-15.233	**0.048
	Purple to red	-10.933	**0.035
Green to blue	Red to Yellow	8.733	0.065
	Yellow to green	7.233	0.183
	Blue to purple	-8	0.289
	Purple to red	-3.7	0.551
Blue to purple	Red to Yellow	16.733	0.011
	Yellow to green	15.233	0.048
	Green to blue	8	0.289
	Purple to red	4.3	0.524
Purple to red	Red to Yellow	12.433	0.017
	Yellow to green	10.933	0.035
	Green to blue	3.7	0.551
	Blue to purple	-4.3	0.524

**The significance level was 0.05.

The analysis of the correlation between total accuracy and speed with Spearman's rank-order correlation test was performed. The results indicated that there was a statistically significant relation between number of correct arrangements and speed of performing hue differentiation tasks (Rs=0.150, P=0.001) (see appendix c1).

4.2.3. Hue differentiation sensitivity of each chip

There was 5% hue level difference between all of the chips in each hue differentiation task. The differentiation sensitivity of each chip was analyzed with standard deviation values in order to investigate the effects of SPD characteristics of light sources on the differentiation sensitivity of chips. SD values showed the scattering of the data from the mean of the chips on each of the hue differentiation tasks. It is known that low SD values show less variability of data and high SD values show more spread of data (Barde & Barde, 2012). In order to investigate the variability of wrong arrangements for 30 samples under each light source, SD values should be larger than 0.298 (Harris, 2007).

SD values indicated that in all of the three light sources, wrong arrangements were near the pure colors. For instance in red to yellow (R to Y) hue chips the wrong arrangements were mostly near red and yellow zones of the hue differentiation task. In order to investigate the relation between the wrong arrangements of the chips with the SPD of the light sources, precise analysis was performed. By dividing each 20-hue chips into five, we have four equal zones to study (see figure 32). Line graph showed that the wrong arrangements in red to yellow (R to Y), blue to purple (B to P) and purple to red (P to R) hue chips were observed mostly in zone 1 and 4 under LED light source. However, in yellow to green (Y to G) and green to blue (G to B) hue chips wrong arrangements were in zone 2 and 3 (see figure 32 and table 17). Under CFL, the wrong arrangements in (R to

Y) and (B to P) hue chips were mostly in zone 1, 3 and 4 while in (Y to G), (G to B) and (P to R) hue chips were just in zone 1 and 4. Under D65 light source, the wrong arrangements in all of the hue chips were in just zone 1 and 4. Under D65 light source, there were not any wrong arrangements in zone 2 and 3 (see figure 38 and table 17).

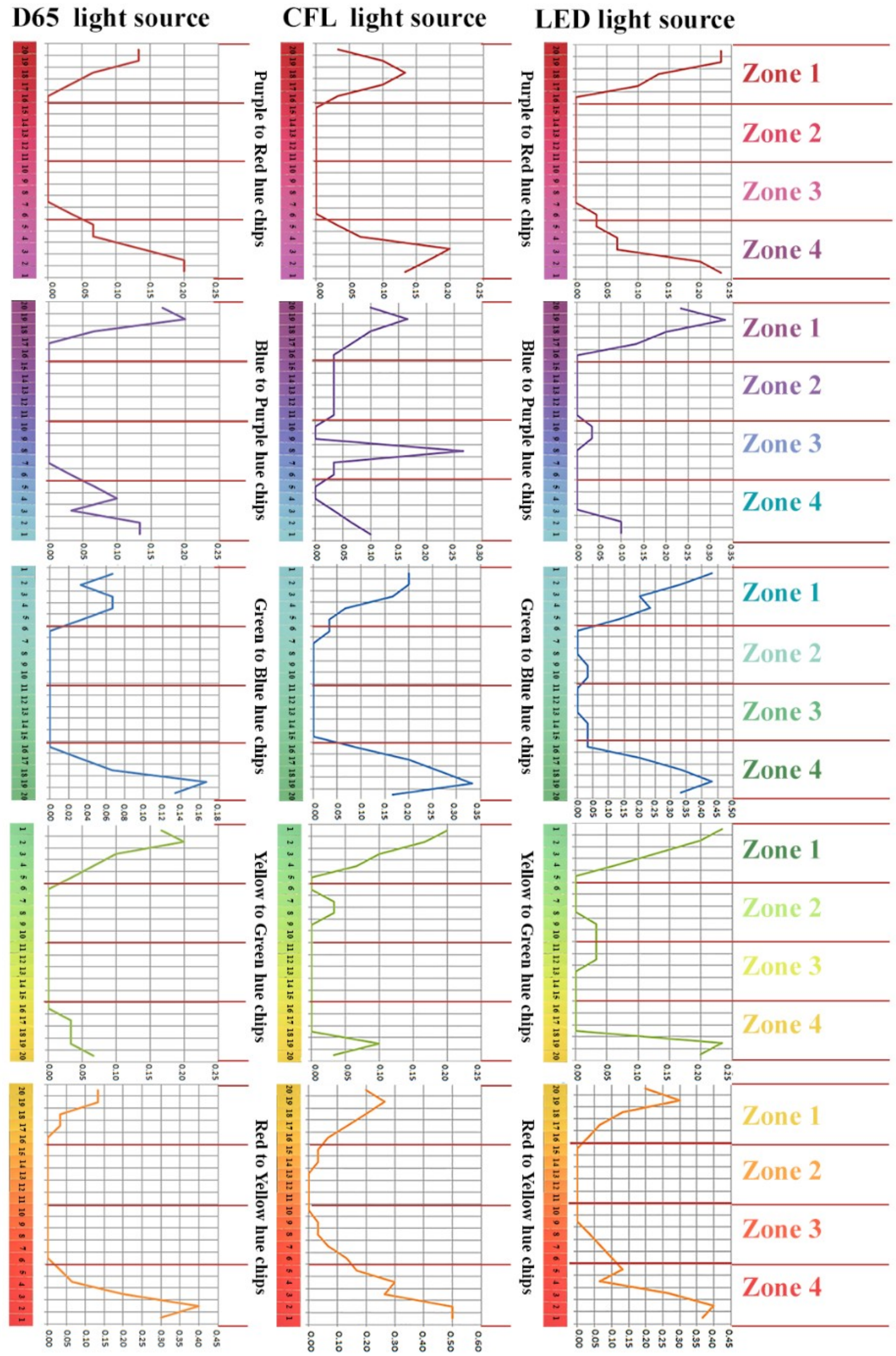

Figure 38: Line graph of hue chips in terms of accuracy under each light source.

Table 17: Standard deviation of each hue color chips

Std. Deviation		Chip 1	Chip 2	Chip 3	Chip 4	Chip 5	Ch														
Red Yellow Hue	LED	0.819	0.699	0.819	0.254	0.712	0.														
	CFL	1.552	1.114	0.664	1.037	0.714	0.7														
	D65	0.621	0.592	0.610	0.263	0.183	0.														
[illegible]	LED	0.596	0.556	0.648	0.403	0.00	0.														

4.2.4. The effects of SPD characteristics on alertness level

The difference in alertness level after exposed to the experiment between light sources with different SPD characteristics was examined. Besides, the difference of alertness level before and after exposed to the experiment under each light source was examined. Alertness level of the participants after exposed to the experiment was observed to be highest under D65 followed by LED and CFL. However, the results of Kruskal-Wallis H rank test showed that the differences in alertness levels after the experiment under different light sources were not statistically significant (chi square= 3.027, p=0.22) (see table 18).

Table 18: Statistical analysis of alertness level after the experiment between light sources

	LED		CFL		D65		Kruskal-Wallis H	
	Mean	Std.	Mean	Std.	Mean	Std.	Chi square	p
Alertness level (after the experiment)	2.57	0.898	2.33	0.711	2.77	0.935	3.027	0.22

**The significance level was 0.05.

Paired sample t-test was performed to investigate the alertness differences before and after exposed to the experiment under each light source. The results showed that there were not any significant differences on alertness level before and after the experiment under LED, CFL and D65 light sources (t=0.273, p=0.787), (t=0.297, p= 0.769) and (t=0.465,p=0.645) respectively (see table 19). Although the alertness level after exposed to the experiment under all of the light sources was lower than before the experiment, the difference was not statistically significant. Besides, under D65 light source the difference between alertness level value before and after exposed to the experiment was higher than other light sources (see table 19).

Table 19: Statistical analysis of alertness level before and after the experiment under each light source.

Alertness level	**LED**		Paired sample T-Test		**CFL**		Paired sample T-Test		**D65**		Paired sample T-Test	
	mean	Std.	**t**	**p**	mean	Std.	**t**	**p**	mean	Std.	**t**	**p**
BEFORE	2.6	0.968	0.273	0.787	2.37	0.756	0.29	0.769	2.83	1.177	0.465	0.645

AFTER	2.57	0.898			2.33	0.711			2.77	0.935		

**The significance level was 0.05.

4.2.5. The effects of SPD characteristics on perceived performance

The difference in perceived performance of participants was examined to investigate the effects of SPD characteristics on perceived performance after exposed to the experiment. The results of Kruskal-Wallis H test showed that there was not any significant difference of perceived performance between three different light sources in terms of overall success, attention to speed and attention to accuracy (Chi square= 0.776, P=0.679), (chi square= 4.647, p=0.098) and (chi square= 2.773, p=0.25) respectively. Although the participants evaluated their overall success highest under CFL followed by D65 and LED, their attention to speed highest under LED followed by CFL and D65, and their attention to accuracy highest under LED followed by D65 and CFL, the differences were not statistically significant (see table 20).

Table 20: Statistical analysis of perceived performance between different light sources.

	LED		CFL		D65		*Kruskal-Wallis H*	
1=poor, 5= excellent	mean	Std.	mean	Std.	mean	Std.	Chi square	p
What you think about your degree of success in the tasks you performed?	3.83	0.53	3.97	0.61	3.87	0.62	0.776	0.679
How much attention did you pay to the speed, in the tasks you performed?	3.93	0.64	3.70	1.08	3.37	1.03	4.647	0.098
	4.63	0.6	4.43	0.6	4.45	0.5	2.773	0.25

How much attention did you pay to the accuracy, in the tasks you performed?		1		2		7		

**The significance level was 0.05.

4.3. Discussion

In this chapter, the significant results of the experimental study and their relation with the information in the literature are discussed with the main issue of the effects of SPD characteristics on hue differentiation performance. This chapter consists of three main headings; the effect of SPD characteristics of different light sources on: accuracy and speed of performing hue differentiation task, on sensitivity of each hue differentiation chips, on alertness level and perceived performance.

4.3.1. The effects of SPD characteristics on accuracy and speed of performing hue differentiation task

The effects of SPD characteristics of light sources on accuracy and speed of performing hue differentiation task were investigated in this thesis. The SPD characteristics of light sources and its effects on different color and visual task performances were examined in the literature. In this thesis the main hypothesis was “The *accuracy* and *speed* of performing hue differentiation task are significantly higher under D65 light source compared to LED and CFL”.

In this experimental study, the statistical analyses were conducted separately for speed and accuracy of performing hue differentiation task. Firstly, the results of this study revealed that total accuracy of hue differentiation task is highest under D65 while compared to LED and CFL. In this study, number of incorrect arrangements in red to yellow (R to Y) hue differentiation chips is significantly lower under CFL followed by LED and D65. Besides, the accuracy of arranging (R to Y) hue differentiation chips is significantly lower while compared to arranging yellow to green (Y to G), blue to purple (B to P) and purple to red (P to R) hue chips under CFL light source. In arranging green to blue (G to B) hue differentiation chips, participants made the lowest accurate arrangements under LED followed by CFL and D65. Besides, the accuracy of arranging (G to B) hue chips is significantly lower compared to yellow to green (Y to G) and blue to purple (B to P) hue chips under LED light source. The results can be due to the wide and continuous SPD characteristic of D65 light source, lower radiation intensities in (G to B) zone in SPD characteristic of LED light source and lower radiation intensity of (R to Y) zone in SPD characteristic of CFL.

These findings support the effects of SPD characteristics of light sources on hue differentiation performance and support the studies in the literature about SPD characteristics of light sources (Broadbent, 2017; Pardo et al., 2012; ; Schupbach et al., 2015; Viénot et al. 2005). According to Broadbent (2017), D65 light source is the simulator of the CIE‘s standard D illuminant. It consists of broad and continuous SPD characteristic and has radiation intensities in every wavelength such as incandescent light sources and this leads to better color differentiation performances. Broadbent (2017) also explained SPD characteristic of white LED light source and CFL. He clarified that LED and CFL have line SPD characteristic, which means that their SPD graph have limited number of radiation intensities on certain wavelengths. SPD graph of white LED light source consists of two peaks and one down relative intensity values. According to information conducted by Broadbent (2017), in this thesis, the reason of higher accuracy in arranging hue differentiation chips under D65 compared to LED and CFL can be due to broad SPD characteristic of D65 and limited number of radiation intensities in SPD graph of CFL and LED light sources.

Additionally the results showed similarity with the study conducted by Pardo et al., (2012). They investigated the fact that distributions of intensities affect the level of excitation of each type of cones. They used same RGBA LED light sources but with different CCTs (2800K, 5000K, 6500K). Their results state that color-distinguishing capacity is better under light sources with higher CCTs. They explained that it is due to the reason that spectral peak in the zone of more intense blues in high CCTs leads to higher absolute level of S-cone excitation. In this thesis same as the results conducted by Pardo et al., (2012), hue differentiation performance was better under D65 which has spectral peak in the zone of more intense blues while compared to LED and CFL with spectral peaks in near red zone.

Schupbach et al., (2015) studied the effects of LED, HID, fluorescent and halogen light sources with the same CCT (3000K) on viewing the illuminated objects. Their results state that LED light source emits more diffuse light pattern in its SPD, which leads to softening effect on the viewing of materials illuminated by it. The results of this thesis support the results of the study conducted by Schubpach et al., (2015). In this thesis, the hue differentiation performance was lowest under LED light source.

The results of the study conducted by Viénot et al. (2005) stated that erros rates are higher in green to blue and blue to purple hue task under LED light source. They explained that the error rates were due to very low radiation intensities in greenish blue and purple shades of LED light source's SPD graph. It was found in this thesis that under LED light source the number of inaccurate arrangements was higher in green to blue (G to B) hue chips. However the number of inaccurate arrangements was in minimum in blue to purple (B to P) hue chips compared to other hue chips. The results of this thesis can more precisely clarified by the information given about RGB LED light source by Viénot et al. (2005). They indicated that error rates in color differentiation task were higher under RGB LED light source while compared to different LED light sources with the same CCTs. They showed that it is due to the peaks and downs in SPD of RGB LED, which leads to low emission in certain zones of the spectrum.

The results of this thesis show differences with the study done by Jiang et al. (2014). In this thesis, number of inaccurate arrangement was highest under LED light sources, which have different peaks in its SPD graph. In contrarily, in the study conducted by Jiang et al. (2014) judged that SPD graphs with more peaks can give better color matching and more saturated effect on mesopic condition. However, they did not concentrate on the effects of down parts in the radiation intensities of a light source's spectrum graph. They studied the effects of spectrum on color visual performance at mesopic condition. High-pressure sodium, RGB LED and phosphor converted white LED light sources were used in their study. They indicated that under RGB LED, that has three peaks on its SPD graph, better color saturated effect and higher color matching performance were observed in mesopic condition.

As mentioned before the statistical analyses of this thesis were conducted separately for speed and accuracy of performing hue differentiation task. The results of statistical analyses for speed of performing hue differentiation tasks showed that there was statistically significant difference in speed of arranging hue differentiation tasks under D65 compared to LED and CFL. Total speed of arranging hue differentiation tasks were highest under D65 followed by CFL and LED light source. The results can be due to SPD characteristics of D65 light source, participants differentiated the hue difference between chips with higher accuracy and faster speed under D65. Under CFL, there was statistically significant difference in terms of speed in arranging red to yellow (R to Y) and yellow to green (Y to G) hue differentiation tasks compared to other hue chips. The speed of arranging (R to Y) and (Y to G) hue differentiation tasks were significantly lower compared to blue to purple (B to P) and purple to red (P to R) hue differentiation tasks under CFL. Under LED light source, there was not any significant difference between hue differentiation tasks in terms of speed.

The results show difference with the study conducted by Shamsul et al., (2013) which showed that speed of typing was better under 4000K than 6500K. They investigated the effects of CCT of light sources on speed of performing computer and paper based visual tasks. They used 3000K, 4000K and 6500K light sources. While in this thesis, the speed of performing hue differentiation task was better under D65 with 6500K CCT compared to CFL and LED light sources with 4000K CCT.

According to the results and their relations with the information in the literature, the main hypothesis of this thesis; “H: The *accurac*y and *speed* of performing hue differentiation task are significantly higher under D65 light source compared to LED and CFL” can be verified.

4.3.2. The effects of SPD characteristics on hue differentiation sensitivity of chips

The hue differentiation sensitivity of chips is also investigated in this study. The results of more precise study among the wrong arrangements in hue chips indicated that in all light sources wrong arrangements where mostly in major hues of Munsell color order system. For instance, the wrong arrangements were mostly in reddish chips than in orange chips in performing red to yellow (R to Y) hue differentiation chips. The results showed that under LED light source wrong arrangements in red to yellow (R to Y), blue to purple (B to P) and purple to red (P to R) hue chips were observed mostly in zone 1 and 4 which are the pure colors. However, in yellow to green (Y to G) and green to blue (G to B) hue chips wrong arrangements besides the zone 1 and 4 were in zone 2 and 3. This is due to the SPD characteristics of the LED light source. Under CFL, the wrong arrangements in (R to Y) and (B to P) hue chips were mostly in zone 1, 3 and 4 while in (Y to G), (G to B) and (P to R) hue chips were just in zone 1 and 4. Under D65 light source, the wrong arrangements in all of the hue chips were in just zone 1 and 4. Under D65 light source, there were not any wrong arrangements in zone 2 and 3. It can be understand that participants had more difficulties than just pure colors in distinguishing (R to Y), (B to P), (Y to G) and (G to B) hue chips under LED and CFL.

The results show similarity with the information in the literature about visual system and its sensitivity to different colors and the factors which can affect color distinguishing ability (Fisher, 1976; Melgosa et al., 2000). The visual system of the people with no color vision deficiencies is more sensitive to hue changes around yellow and borders of blue-green and it can distinguish these colors better than other ones. However, it has difficulties in two last part of the spectrum graph, which correspond to purple and red colors. There should be a large change in wavelength in order to detect a difference in hue of red colors but for most of the other colors almost 2 nm difference in hue is enough for detecting the change in color (Fisher, 1976) . The results are also in association with the experiment performed by Melgosa et al. (2000) which they examined that large hue differences were better for color differentiation, but in this dissertation as hue difference level was 5% it leads to lower color identifications in major Munsell colors of hue chips such as red or yellow chips. However, in the middle parts the hue chips arrangements were higher and it can be due to the constant hue changes of those parts as mentioned by Melgosa et al. (2000).

According to the results and their relations with the information in the literature, the other hypothesis of this thesis; “H1a: The hue differentiation chips are sensitive to SPD characteristics of the light sources.” can be verified.

4.3.3. The effects of SPD characteristics on alertness level and perceived performance

The results indicated that SPD characteristics of different light sources did not affect the alertness level of the participants. The mean of alertness level of the participants after exposed to the experiment were higher under D65 but this value was not statistically significant while compared to CFL and LED light sources. These results are similar to the previous studies about alertness level. According to literature, exposure to short wavelength blue lights (l max ~ 480 nm) lead to an enhancement in mood, alertness and performance (van Bommel & van den Beld, 2004; Linhart & Scartezzini, 2011; Papamichael et al., 2012; Chang et al., 2013; Bourgin & Hubbard, 2016). Also the results of this dissertation are similar to the study done by Chellappa et al. (2011) which examined that 6500K light source increased the subjective alertness level, cognitive performance and sustained attention in comparison to 2500K and 3000K light sources. It was due to the high amount radiation in blue intensity in SPD of 6500K.

Additionally participants self-reported answers to their perceived performance were not significantly different under different light sources. Although the reported accuracy and success were higher under D65, the results of expected success were not different under different light sources.

According to the results and their relations with the information in the literature, the other hypotheses H1b and H1c cannot be verified (see section 3.1.1) H1b hypothesis is that

"There is significant difference in the alertness level of the participants after being exposed to the experiment under light sources with different SPD characteristics". H1c hypothesis is that "There is significance difference in perceived performance of the participants after being exposed to the experiment under light sources with different SPD characteristics".

CHAPTER V

CONCLUSION

The effects of SPD characteristics of different light sources on hue differentiation task were investigated in a light booth as a controlled situation. A questionnaire was designed to investigate the effects of SPD characteristics of light sources on alertness level and perceived performance. The experiment was conducted under D65, LED and CFL, which have different SPD characteristics. The hue attribute of the color was used for differentiation task performance. Hue differentiation task model designed by Kurkcu (2017) was used in this study. Studies in the literature state that our visual system is a trichromatic system, so that we can see all the white lights the same. However, they may consist of different SPD characteristics. These differences can have effects on the visual performances especially on the appearance of the colored objects. Regarding these issues there is need to understand whether broader, continuous or narrowband wavelength light sources are required in order to complete the color oriented tasks in office workspaces.

As mentioned in the literature part hue is the attribute of the color that varies according to spectrum. The relationship between the wavelength of the special hue and perceived color is not an absolute relationship. In the studies about the effects of light sources with different SPDs on the perception of materials, brightness color and different color tasks, we can see that there is not any straightforward relationship. However, from these studies we can understand that the relationship is tied and task performance or brightness values of colored objects can be explained through the SPD characteristics of the light source, human visual system and the spectral reflectance of the colored objects.

D65, CFL and LED light sources were used in this study. D65 has a broad and continuous SPD characteristics which covers huge radiation intensity same as incandescent lamps. According to previous studies, incandescent lamps have better color fidelity observation in comparison to line spectra light sources. CFL and LED light source are line spectra light sources, which mean their radiation intensities are, differ in different parts of their SPD. They have peaks and downs, in upper parts, the intensity of corresponding monochromatic color is higher and in the down parts, the intensity of the monochromatic color is lower.

The findings showed that; the speed and accuracy of performing hue differentiation task was significantly higher under D65 light source compared to CFL and LED, SPD characteristics of light sources affected the hue differentiation sensitivity of each chips and SPD characteristics of the light sources did not affect the alertness level and perceived performance of the participants.

There are some limitations in the experimental study of this thesis. First limitation was that the experiment conducted in a controlled situation in order to prevent any environmental issue but the results may have some difference from a real office environment and the participants were not real office workers. Second limitation is that we could not measure the spectral reflectance of the colored hue chips. Third limitation was that the effects of general lighting inside the experimental room were eliminated by turning off the general lighting.

For further studies, concentration on demographics such as age, gender and department can be done. Because genders can have differences in color differentiation capacities and department of the students also can be effective on their information about the colors. Since the participants were chosen from Bilkent and Middle East Technical Universities, their ages were in almost the same range and effects of the age could not be studied.

Number of the female and male students that were contributed in the experiment was not the same also. Besides, the reflectance SPD of the illuminated object should also study in the future for investigating the effects of SPD characteristics on the hue differentiation performance. In this study just one LED, CFL and D65 light source were used. For further studies, different LED and CFL and CIE illuminants can be examined.

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APPENDICES

Appendix A. Questionnaire of the study

This survey is to obtain data for a master thesis titled "Effects of energy efficient task light sources on readability and subjective preferences" at Bilkent University, Department of Interior Architecture. The data gathered will not be used for any other purposes and will not be published. Thank you for your participation.

The first part of the questionnaire consists of questions about personal info. The second part consists of questions related with evaluating your own performance and your *preferences. The third part consists of Karolinska Sleepiness Scale (KSS) for evaluating your alertness.*

1. **Personal Info**

Name/Surname:

Age:

Gender**:** F □ M □

Department**:**

1. **Indicate which level best reflects the psycho-physical state you are experiencing right now before starting the tasks.** (Karolinska sleepiness scale KSS, Akerstedt and Gillberg , 1990).

Extremely alert	1
Very alert	2
alert	3
Rather alert	4
Neither alert nor sleepy	5
Some signs of sleepiness	6
Sleepy, but no effort to keep awake	7
Sleepy, but some effort to keep awake	8
Very sleepy, great effort to keep awake	9

2. **Select the appropriate value for each question to evaluate your visual performance.**

	Poor	Fair	Good	Very good	Excellent
What do you think about your degree of success in the tasks you performed?	1	2	3	4	5

How do you rate your speed, in the tasks you performed?	1	2	3	4	5
How much attention did you pay to accuracy, in the tasks you performed?	1	2	3	4	5

3. **Indicate which level best reflects the psycho-physical state you are experiencing right now at the end of the test.** (Karolinska sleepiness scale KSS, Akerstedt and Gillberg , 1990).

Extremely alert	1
Very alert	2
alert	3
Rather alert	4
Neither alert nor sleepy	5
Some signs of sleepiness	6
Sleepy, but no effort to keep awake	7
Sleepy, but some effort to keep awake	8
Very sleepy, great effort to keep awake	9

Appendix B. Photographs of the Experiment Setup and Color Tasks

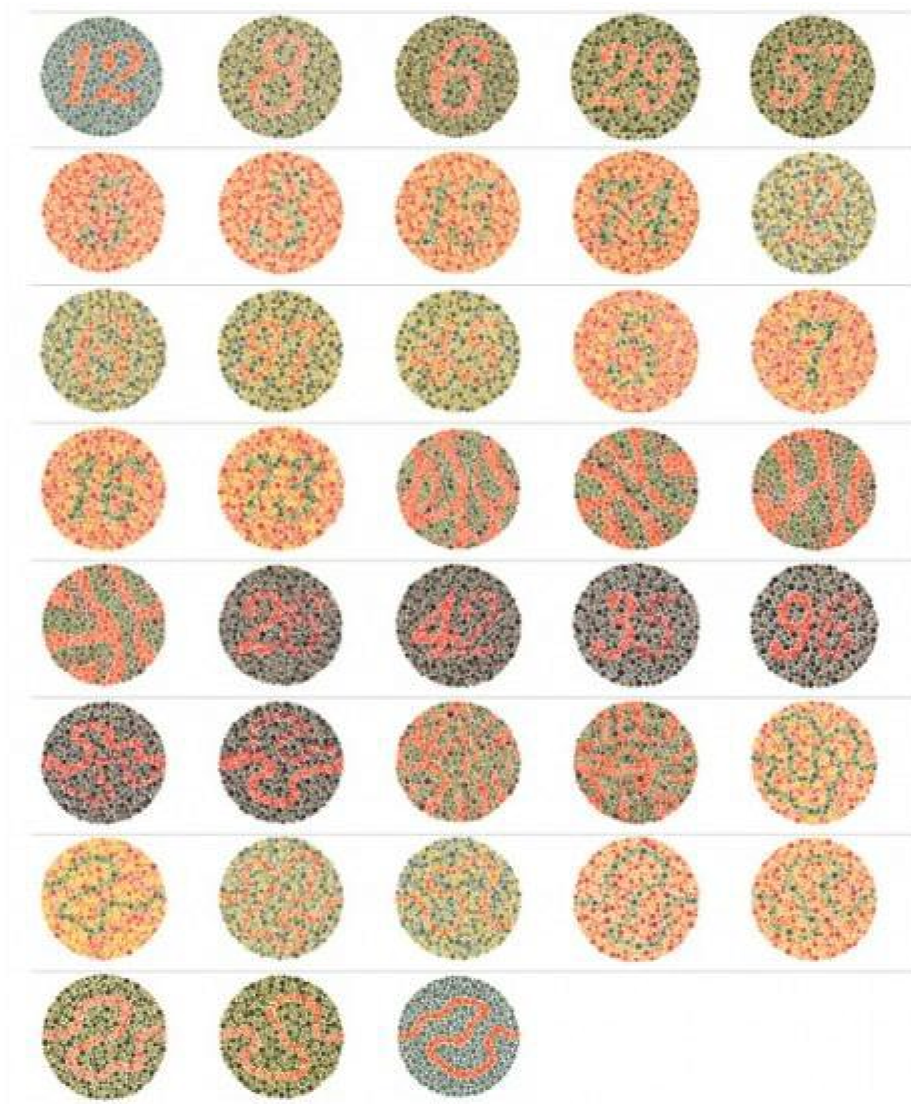

Figure B1: Ishihara Color Blindness Test

(Source: [http://www.color-blindness.com/ishiharas-test-for-colour-deficiency-38- plates-edition/](http://www.color-blindness.com/ishiharas-test-for-colour-deficiency-38-plates-edition/))

Figure B2: Panoramic photograph of the experiment room (lighting laboratory).

Figure B3:Left: Light booth while the general lighting and lighting inside the light booth turned on. Right: light booth while the general lighting turned off.

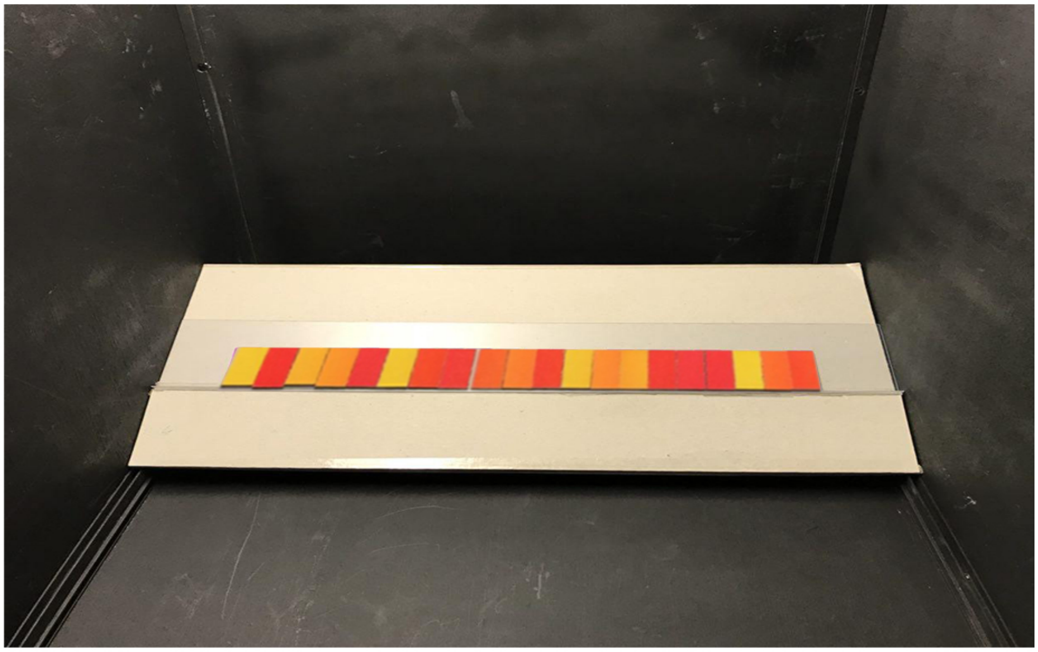

Figure B4: Red-Yellow Hue Differentiation Task

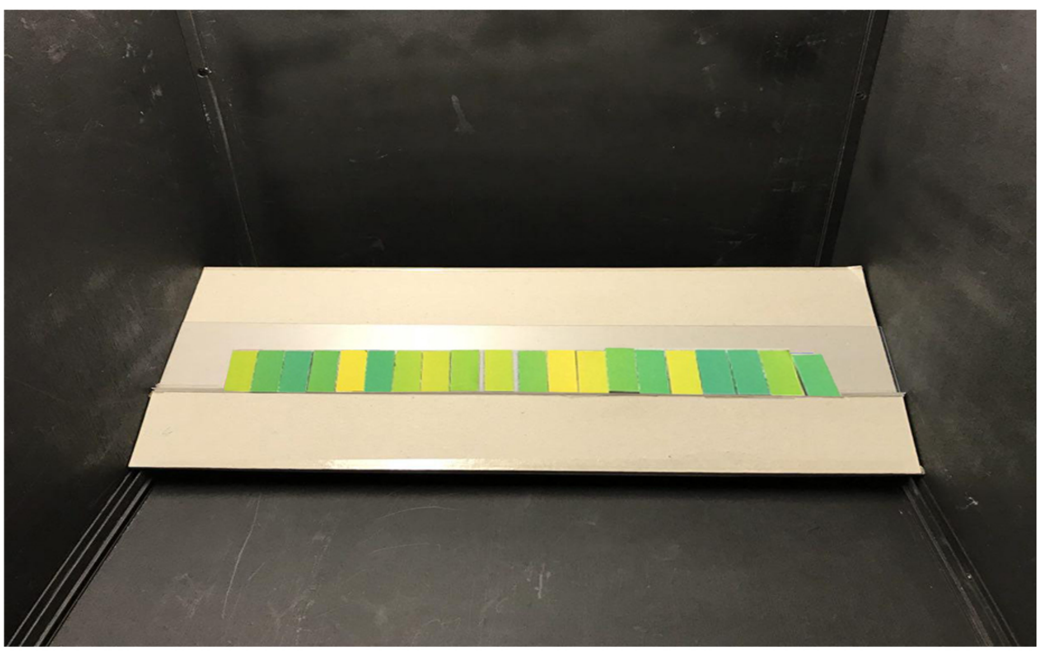

Figure B5: Yellow-Green Hue Differentiation Task

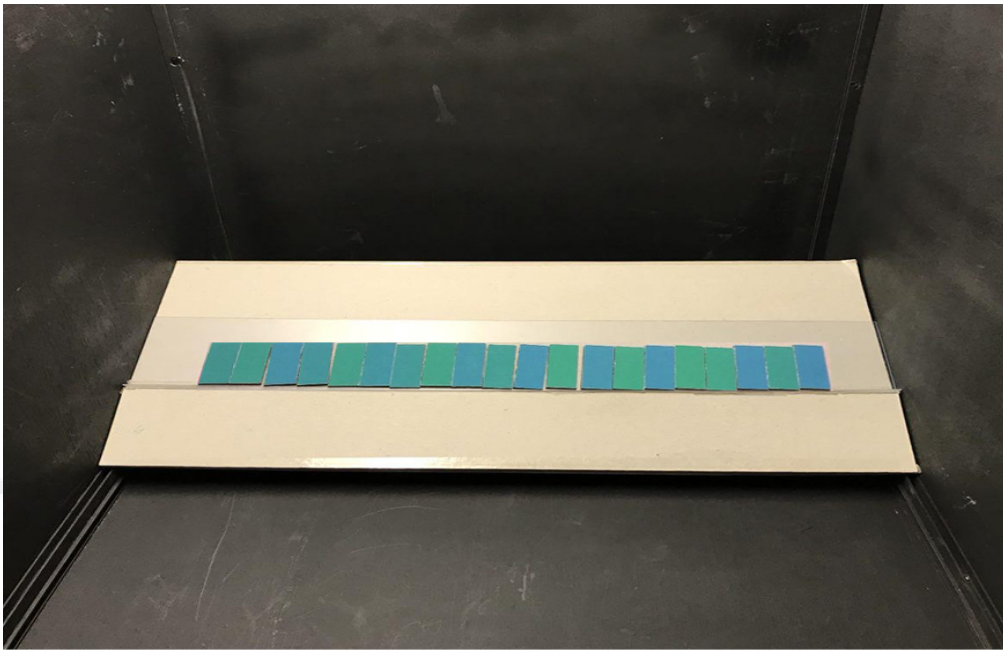

Figure B6: Green-Blue Hue Differentiation Task

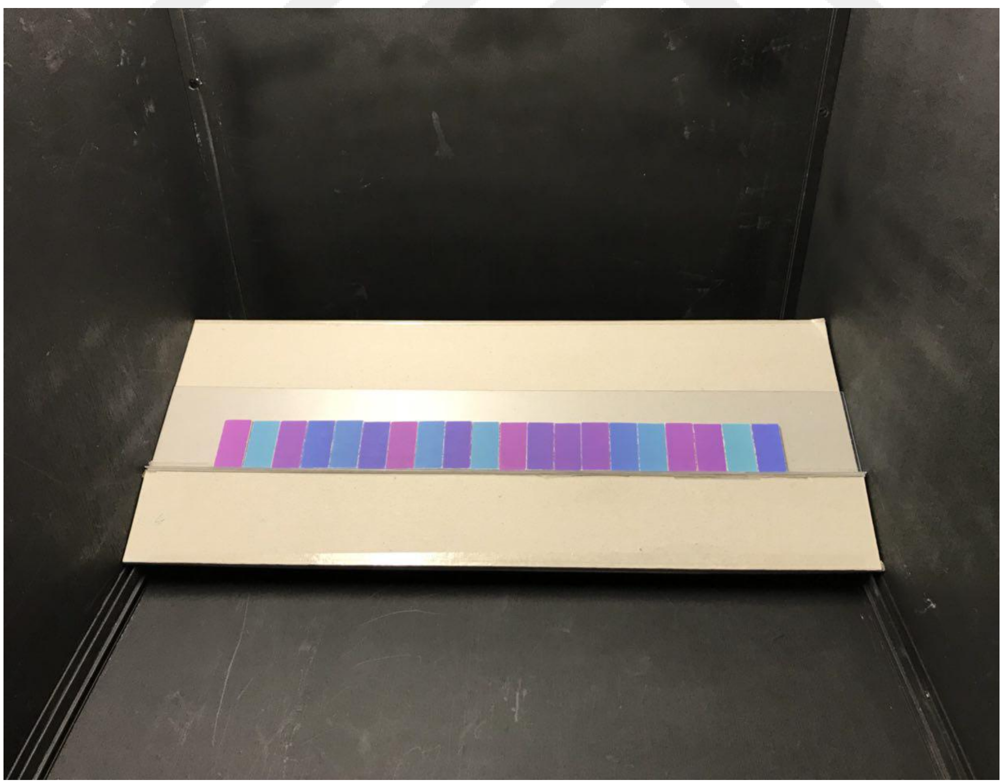

Figure B7: Blue-Purple Hue Differentiation Task

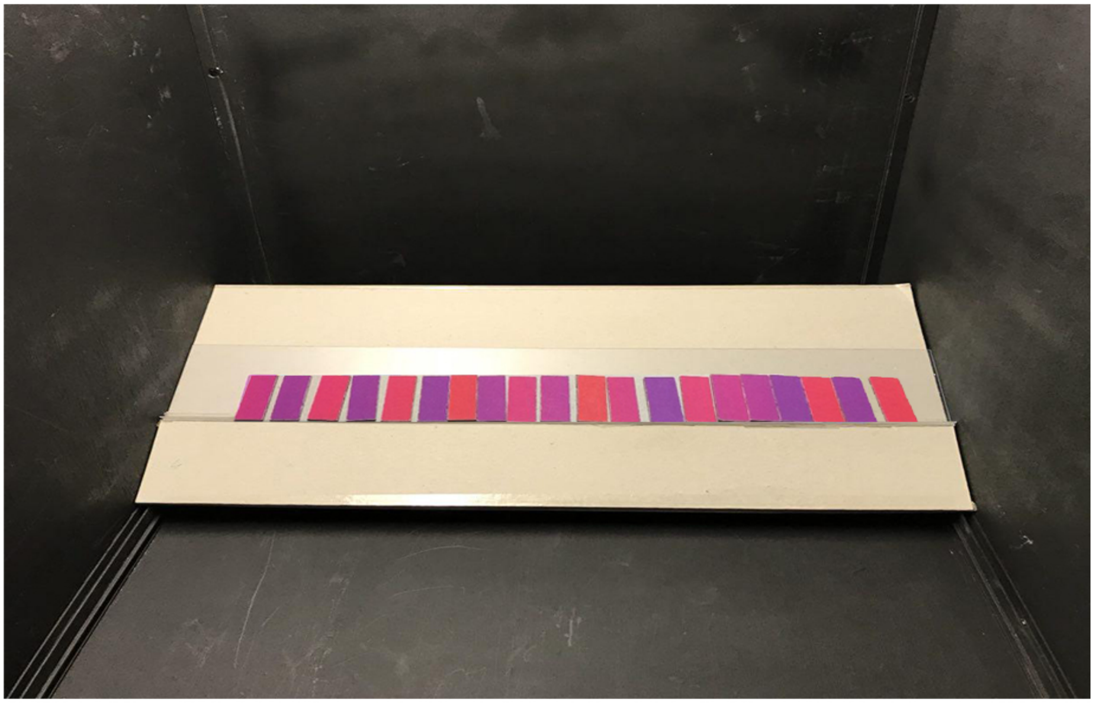

Figure B8: Purple-Red Hue Differentiation Task

Appendix C. Statistical analysis and bar charts.

Correlations

			accuracy_total	Time_total
Spearman's rho	accuracy_total	Correlation Coefficient	1.000	.150**
		Sig. (2-tailed)	.	.001
		N	450	450
	Time_total	Correlation Coefficient	.150**	1.000
		Sig. (2-tailed)	.001	.
		N	450	450

**. Correlation is significant at the 0.01 level (2-tailed).

Figure C1: Statistical analysis of correlation between total time spent and accuracy.

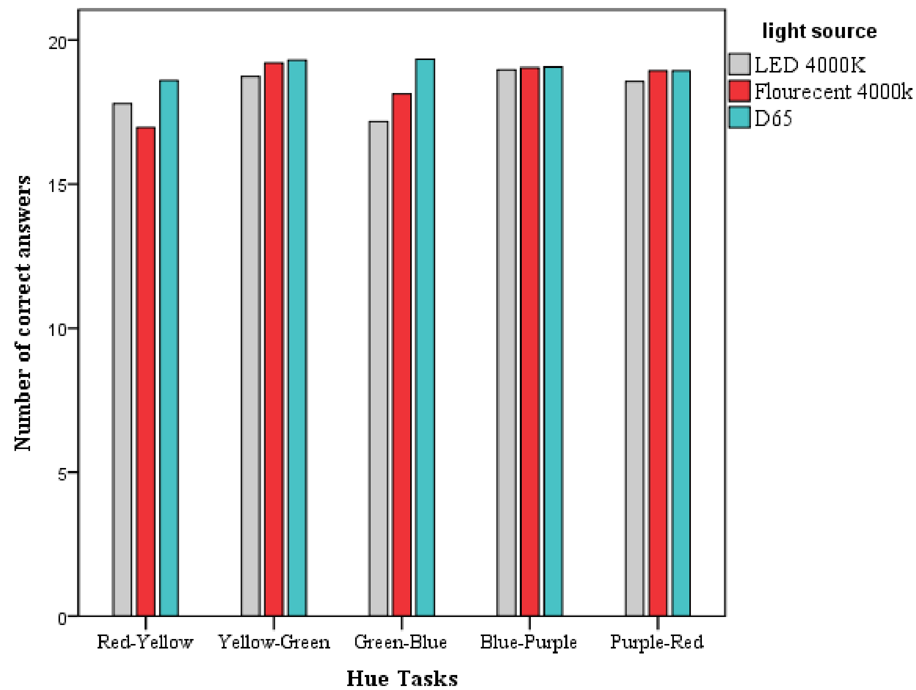

Figure C2: Bar graph of each hue task differences in terms of accuracy under different light sources.

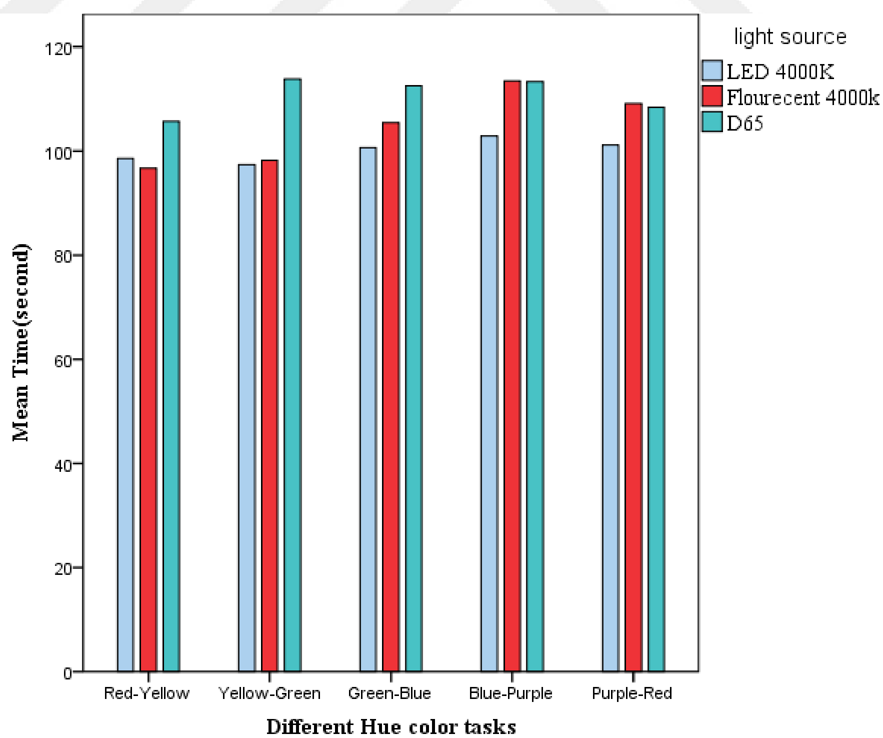

Figure C3: Bar graph of each hue task differences in terms of Speed under different light sources.

Figure C4: Mean value of accuracy between hue differentiation chips.

Mean value		Chip 1	Chip 2	Chip 3	Chip 4	Chip 5	Chip 6	Chip 7	Chip 8	Chip 9	Chip 10	Chip 11	Chip 12	Chip 13	Chip 14	Chip 15	Chip 16	Chip 17	Chip 18	Chip 19	Chip 20
Red-Yellow Hue	LED	1.53	1.83	2.87	3.93	4.9	5.97	7	7.97	9	10	11	12	13	14	15	16.07	16.03	18.07	19.1	19.80
	CFL	2.07	2	2.8	3.6	4.8	5.83	6.9	8.03	8.97	10	11	12	13	14.03	14.97	16.07	17.00	18.10	19.07	19.77
	D65	1.4	1.83	2.8	4	4.97	4.97	7	8	9	10	11	12	13	14	15	16	16.98	18.03	19.07	19.80
Yellow-Green Hue	LED	1.30	1.97	2.83	3.90	5	6	7	8.00	9.03	9.97	11.03	11.97	13	14	15	16	17	18	19.17	19.80
	CFL	1.23	1.83	3	3.93	5	6	7.03	7.97	9	10	11	12	13	14	15	16	17	18.07	18.97	19.97
	D65	1.20	1.87	2.97	4	4.97	6	7	8	9	10	11	12	13	14	15	16	17.03	17.97	19.07	19.93
Green-Blue Hue	LED	1.57	1.77	2.80	4	4.87	6	7	8	9.03	9.97	11	12	13	14.03	14.97	16.03	17.13	18.07	19.10	19.57
	CFL	1.33	2.10	2.77	3.80	5.03	5.97	7	8	9	10	11	12	13	14	15.03	16.03	17.10	18	19	19.83
	D65	1.10	1.97	2.97	4	4.97	6	7	8	9	10	11	12	13	14	15	16	17.03	18	19.10	19.87
Blue – Purple Hue	LED	1.10	1.90	3	4	5	6	7	8	9.03	9.97	11	12	13	14	15	16	17.17	17.93	19.13	19.77
	CFL	1.13	1.93	2.93	4	5	6.03	6.97	8	9	10	11.03	11.97	13.03	13.97	15.10	16.03	16.97	17.97	19.03	19.90
	D65	1.20	1.87	2.97	4.03	5	5.93	7	8	9	10	11	12	13	14	15	16	17	18.07	19.13	19.80
Purple-Red Hue	LED	1.40	1.90	2.97	3.90	4.87	5.97	7	8	9	10	11	12	13	14	15	16	17.10	17.93	19.23	19.73
	CFL	1.20	2.03	2.80	4	4.97	6	7	8	9	10	11	12	13	14	15	16.03	17.03	18	18.97	19.97
	D65	1.27	1.93	2.80	4.07	5	5.97	7	8	9	10	11	12	13	14	15	16	17.07	17.93	19.13	19.87