Colour Discrimination Ability under Fluorescent and Light Emitting Diode

Ai-Hong Chen*, Fazrin Mazlan and Saiful-Azlan Rosli

Optometry, Faculty of Health Sciences, Universiti Teknologi MARA (UiTM), 42300 Puncak Alam, Selangor Malaysia

ABSTRACT

This article aims to quantify the colour discrimination ability by using Total error scores (TES) to categorise colour discrimination level into superior, average or inferior levels under three different types of light sources, with different spectral power distribution. Colour discrimination was investigated using Farnsworth-Munsell 100 hues and compared upon three light sources: compact fluorescent light (CFL), fluorescent light (FL) and light emitting diode (LED). Total error score calculated and pattern of colour caps misplacement plotted used the web-based scoring method (http://www.torok.info/colorvision/fm100.htm). Total error score (TES) for three types of light sources (TES for LED 58.00 ± 18.67, FL 80.00 ± 19.27 and CFL 127.25 ± 28.02) were significantly different [One-way ANOVA (F=9.98, P<0.05)]. Tukey post hoc analysis showed that there was significant difference between compact fluorescent light & fluorescent light, and between compact fluorescent light & light emitting diodes. Variation of the mid-point cap was smaller for both types of fluorescent lights but higher under light emitting diodes. Fluorescent light and light emitting diode with 4000K correlated colour temperature showed average colour discrimination with mean total error score range between 20 to 100, while compact fluorescent light showed inferior colour discrimination with mean total error score of more than 100. Different light sources with different spectral power distributions affected the colour discrimination differently. This cross-over study design using the same subjects, the same testing tool and the same examiner suggested that subject responded differently towards fluorescent light and light emitting diode light source in the total error score of the Farnsworth-Munsell 100 hues.

INTRODUCTION

An important aspect of lighting design is obligatory to minimise the amount of

electricity consumed, for both financial and environmental reasons (Bridger, 2003). The vast growing innovation and technology today emphasises lighting that enhances the productivity of task performance and cost efficiency. Light emitting diodes (LED) light has gradually substituted the conventional fluorescent light (FL) for its cost efficiency and longer lifespan, but its visual impact remains inconclusive. Due to the close link between lighting and visual ergonomic, a comprehensive strategy for lighting design is essential to protect significant benefits, money and human resources (SLL CIBSE, 2009). Despite the variation in lighting application under different circumstances such as industrial, office, hospital, and retail settings, all share three similar objectives in different situations including to facilitate quick and accurate work, to contribute to the safety of those doing the work and to create a comfortable visual environment (The Society of Light and Lighting, 2012). Retail lighting emphasises a balance between general lighting, accent lighting and display lighting to convey the important business message to consumers if the business aims for budget or highly exclusive customers. Lighting for industry depends on the nature of visual information required to undertake work in different industries (Faulkner & Murphy, 1973). Similarly, lighting in the hospital is also functional based (Dalke et al., 2006). The most important function is to meet the task requirements in each area of the hospital. Some of the tasks require high levels of visual performance for the safety of patients. Light can influence human emotions and feelings of well-being. Appropriate lighting in the hospital can increase harmony and competency within the hospital (SLL CIBSE, 2009).

The effect of lightings on colour perception is undisputable. Illuminants A, B, and C were introduced in 1931 by the International Commission on Illumination (CIE), with the intention of respectively representing average incandescent light, direct sunlight, and average daylight (Schanda, 2015). Illuminant D represents phases of daylight, Illuminant E is the equal-energy Illuminant, while Illuminants F represents fluorescent lamps of various compositions. Daylight illumination or Illuminant C is recommended for all colour vision tests. The replacement of LED light source from the conventional light source may have an impact on the quality of life (Ryckaert, Smet, Roelandts, Van Gils, & Hanselaer, 2012). Light source plays an important role in colour discrimination ability, performance and comfort (Boyce & Simons, 1977). Due to its broad spectral characteristics, natural daylight can be used in any visual tasks that need precise colour discrimination ability (Birch, 2001).

The aim of the study was to compare the effect of three types of light with different spectral power distribution (SPD) on colour discrimination. The Farnsworth-Munsell 100 hue test (F-M 100 Hue) was originally designed to test hue discrimination among people with normal colour vision and to measure the areas of colour confusion in colour-defective observers (Farnsworth, 1957). Caps for the centre of confusion zones were used to characterise the major axis of congenital colour defects (Farnsworth, 1943, 1957; Verriest, 1963). The F-M 100-hue test is a chromatic discrimination where the total error score is correlated with the matching range on the anomaloscope and with the wavelength discrimination function a test of the wavelength difference is needed for an observer to detect colour difference (Lakowski, 1971). The F-M 100-hue test was not designed for the screening of colour defect (Birch, 2001). Error scores
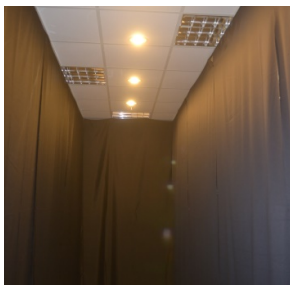
for normal observers should be classified only in three categories (superior, average, and inferior) (Farnsworth, 1957) and can be compared to population statistics (Aspinall, 1974; Kinnear, 1970). A change in score is significant at 0.05 level if the difference of the square roots exceeds 2.27 and at 0.01 level, if the difference exceeds 2.99 (Aspinall, 1974). Therefore, F-M 100-hue test was used in our study to quantify the colour discrimination ability by using error scores to categorise the colour perception as superior, average or inferior level under three different lightings.

MATERIALS AND METHOD

The study was carried out in a windowless $6.0 \times 4.5 \times 3.0$ m room dimension at Optometry and Visual Science Research Centre (iROViS) UiTM Selangor, Malaysia. The room was separated into three partitions using black coloured curtains, as in Figure 1, to minimise the interference from the surrounding surface colour. Due to the wavelength absorption properties of black that might result in dimmer surroundings, the researchers ensured the level of light was maintained within the range of illumination recommended for libraries and residential reading (Schwartz, 2010). Black curtain helped to reduce the surface reflectance to minimise glaring effect. Each partition was installed with different light source: partition 1 had compact fluorescent light (CFL), partition 2 had tubular fluorescent light (FL), and partition 3 was installed with tubular light emitting diode (LED). The characteristics of these light sources are shown in Table 1. Each light source was measured for their illumination and spectral power distribution (SPD) using Lutron LX 101-A and Konica Minolta CL-500A respectively. Illuminance meter (Lutron LX 101-A) and illuminance spectrophotometer (Konica Minolta CL-500A) were positioned in the middle of the working plane which was 2.33 m from the light source. Three readings were taken and averaged from each light source illumination. Meanwhile, the illuminance spectrophotometer (Konica Minolta CL-500A) was connected to a personal laptop. The spectral power distribution graph was automatically tabulated using Konica Minolta CL-S10w software once the readings were taken. FL sources showed similar SPD pattern compared to LED, but the peak wavelengths were different. Correlated colour temperature (CCT) was one of the characteristics of light. CFL was categorised as warm white (2927K). Both FL and LED were grouped as natural white (4000K). The spectral power distribution (SPD) pattern for both CFL and FL peaked at three dominant wavelengths, while LED displayed two dominant wavelengths. Fluorescent lights recorded three highest peaks at 544, 611 and 436 nm, in sequence, respectively, with the spiked bandwidth around 434 to 444 nm, 531 to 558 nm and 603 to 634 nm. For the LED, there were two broad wavelength peaks, 595 and 451 nm, with the broader bandwidth around 431 to 468 nm and 488 to 726 nm as in Figure 2.

Table 1
*Summary of the three light source characteristics*

Light source	Compact fluorescent light (CFL)	Fluorescent light (FL)	Light emitting diode (LED)
Brand	SYLVANIA	SYLVANIA	GE
Model	E27	T8 4FT Fluorescent	T8 4FT LED
Watt	25W	36W	16W
Correlated colour temperature (CCT)	2927K	4000K	4000K
Colour Rendering Index (CRI)	80	82	84
Peak wave-length	512.0 nm	545.0 nm	577.5 nm
Illumination	220 Lux	440 Lux	319 Lux

(a) Compact fluorescent light (CFL)
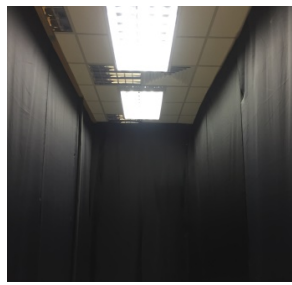
(b) Fluorescent light (FL)
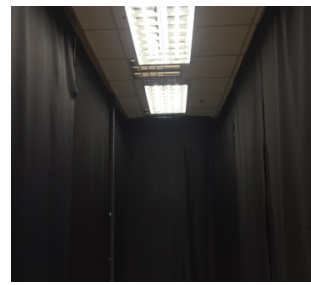
(c) Light emitting diodes (LED)

Figure 1. Three Types of Lighting Set Up in the Experimental room: (a) Compact fluorescent light (2927K); (b) Fluorescent light (4000K); and (c) Light emitting diode (4000K)
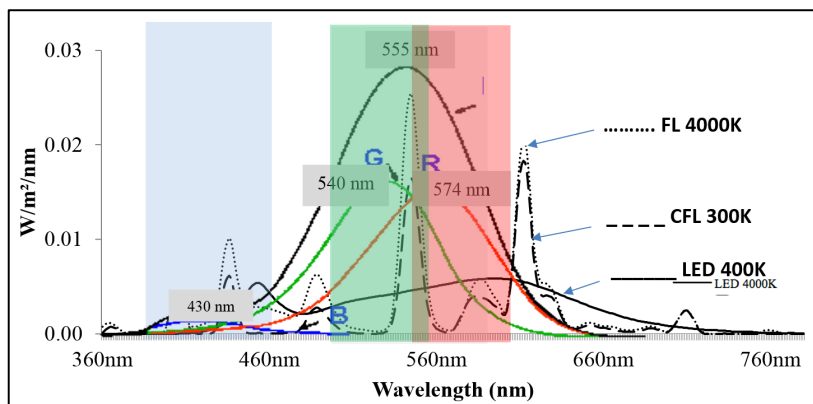

Figure 2. Spectral power distribution of three light sources: 3000K compact fluorescent light (CFL), 4000K fluorescent light (FL) and 4000K light emitting diodes (LED)

These light sources were embedded with relative human spectral sensitivity on cone (555 nm), blue (430 nm), green (540 nm) and red photoreceptor (575 nm) sensitivity. Blue tint area was for blue sensitivity, green tint area was for green sensitivity, red tint area was for red sensitivity, and green and red for photopic sensitivity (Adapted from (Mann, 2011).

Ethical approval was obtained (reference number 600-FSK(PT5/2) from the UiTM ethical committee. To quantify the colour discrimination ability using the different light source, four subjects with mean age of 28±2.27 years were recruited. A preliminary assessment was conducted to ensure that the subject met the selection criteria (age range of 19 to 38 years old, with distance and near visual acuity of 6/6 or better, no known ocular disease and colour vision defect). D-15 colour vision screening was used to rule out any colour deficiency. Informed consent was obtained before participation. Each subject was exposed to three lighting conditions in one visit and five minutes of dark and light adaptation were allocated in between lighting conditions. In order to stabilise the rod and cones photoreceptor sensitivity from previous lighting, light adaptations denoted the wash off period in between the tests. These were evidenced in previous studies that applied at least five to 10 minutes of light adaptation or resting. Bernecker, Davis, Webster, and Webster (1993) tested the effects of several task lighting on visual comfort and five minutes of resting was allocated. Boyce, Akashi, Hunter, and Bullough (2003) allocated 10 minutes of adaptation in their study on the effect of four lighting conditions near visual acuity. Five minutes of adaptation was allocated by Berman, Navvab, Martin, Sheedy and Tithof (2006) in their investigation on near visual acuity under three lighting conditions. Zahiruddin, Banu, Dharmarajan and Kulothungan (2010) also examined the effect of two lighting illumination on colour vision with five to 10 minutes of resting in between the test. Thus, the 10 minutes total of lighting adaptation should be sufficient as wash out period for eye sensitivity to stabilise and at the same time providing time for subject to rest. The testing procedure began with five minutes of dark adaptation and followed by five minutes of light adaptation, before the administration of F-M 100 Hue, as the washing period. Colour discrimination was tested at different light source using F-M 100Hue at random sequence. F-M 100 Hue consists of 85 movable colour testers with a diameter of 1.2 cm arranged in a sequential hue in four boxes of 21 or 22 colours each. The testers were chosen to represent perceptually equal steps of hue and to form a natural hue circle. The colours were set in plastic caps and subtend 1.5° at 50 cm. They were numbered on the back according to the correct colour order of the hue circle. Two referenced colours were fixed at either end of each box. The results obtained were recorded and the total error score (TES) colour cap misplacements were calculated and plotted in F-M 100 Hue online software (http://www.torok.info/colorvision/fm100.htm). The number of colour caps were arranged in sequential circular form in the middle of the recording sheet, as in Figure 3, while middle six colours (red, yellow, green, cyan, blue and purple) were the colour transitions between colour caps. Each line indicated the colour caps wavelength, written outside the recording sheet in nanometres (nm). The dotted lines showed three distinct main rings that classified the colour discrimination scoring - the further the pattern away from the middle ring (higher spikes) showed lower discrimination ability. The graphic representation of colour vision defect findings for protanomaly, deuteranomaly and tritanomaly were also illustrated in Figure 2. The mid-points colour caps range for protanomaly, deuteranomaly, and tritanomaly were 62-70, 56-61,

and 46-52 respectively (Farnsworth, 1957). Each type of colour defect showed a similar trend of colour cap confusion arrangement according to the mid-point, an arrow represented in the circle. The TES pattern was interpreted and analysed to determine which light source showed more superior colour discrimination ability, average or inferior discrimination ability. The total duration required for each subject was approximately 50 minutes. SPSS Version 21.0 software was used to analyse all the descriptive and comparison data.
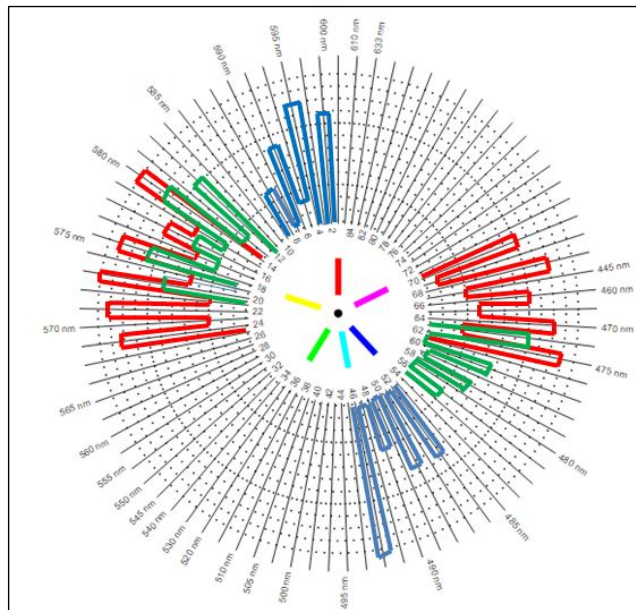

Figure 3. Graphical interpretation of colour deficiency conditions

Protanomaly is represented by red line, deuteranomaly is represented by green line, while tritanomaly is represented by blue line.

RESULTS

One-way ANOVA revealed a significant difference in the total error score for three different light types [$F_{(2, 9)} = 9.98$, $p<0.05$)]. LED demonstrated the best total error score 58.00 ± 18.67, followed by FL with 80.00 ± 19.27 TES. CFL showed the worst TES (127.25 ± 28.02). Tukey post hoc analysis revealed significant mean differences of TES between CFL and LED [(69.25 TES), 95% CI (25.30 to 113.470)] and between CFL and FL [(47.25 TES), 95% CI (3.03 to 91.47)]. The trend of mid-point colour caps was found to be different between FL and LED. Mid-point position was related to the type of colour defect. No major axis of congenital colour defects was detected that mimicked the pattern of protanomaly, deuteranomaly and tritanomaly. Even though there was no specific colour deficient pattern, the trend of colour caps confusion variation was similar in CFL and FL, but different in LED. The variation of the mid-point cap was higher for both types of fluorescent lights [colour cap in of F-M 100 hues ranged from 29 to 34 (500 nm-574 nm)]. More square opaque was found in Figure 4(a)

and 4(b). High calculated TES represented more colour confusion. Lower variation was found among the same subjects under LED [colour cap ranged from 8 to 76 [(400-499nm) & (573-634nm)], with less square opaque as in Figure 4(c). Low calculated TES represented least colour confusion. A normal colour vision perception may differentiate between primary colours (red, green, and blue) but individual colour discrimination may vary at different saturation, as in Figure 5. Thus, the range of variation in the mid-point caps at different light source may predict the pattern of colour confusion among normal.
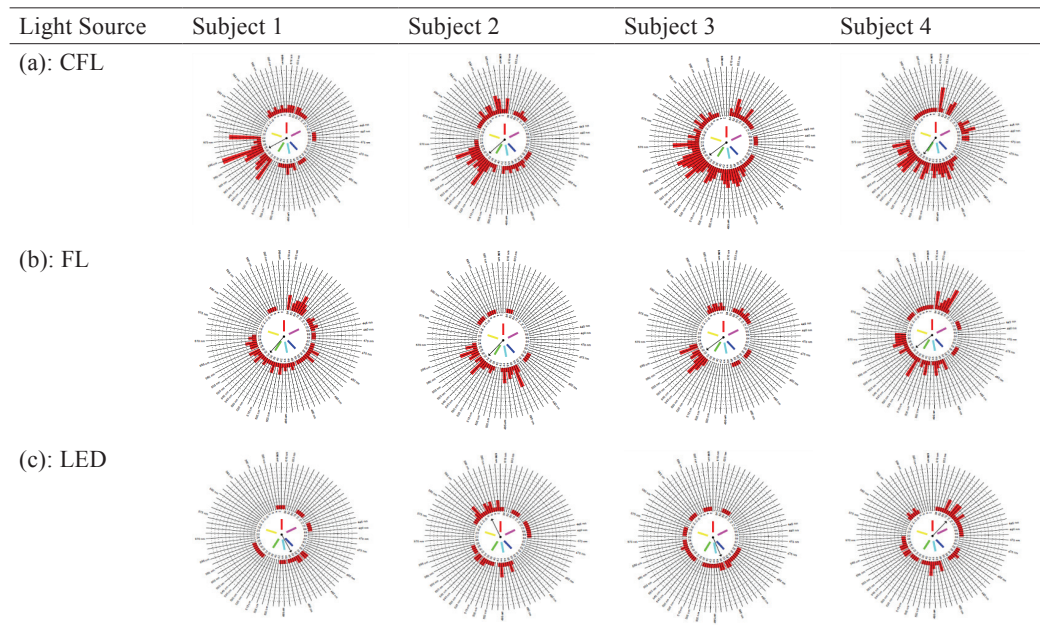
Light Source	Subject 1	Subject 2	Subject 3	Subject 4
(a): CFL				
(b): FL				
(c): LED				

Figure 4. Graphical interpretation of colour vision using: (a) Compact fluorescent light (CFL); (b) Fluorescent light (FL); and (c) Light emitting diodes (LED) (http://www.torok.info/colorvision/fm100.htm)
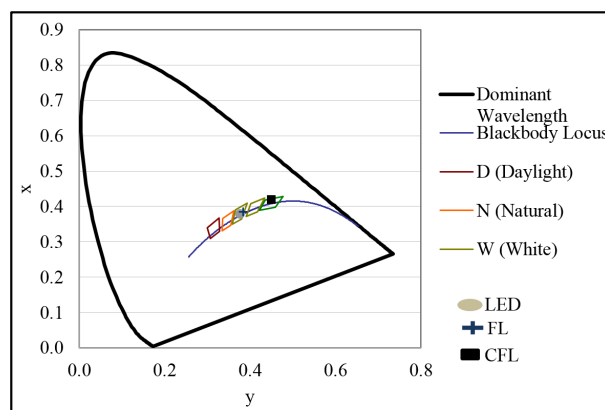

Figure 5. Chromaticity coordinates of compact fluorescent light (CFL), fluorescent light (FL), and light emitting diodes (LED)

The figure above was plotted according to the 1931 CIE Chromaticity Diagram. Each coloured box was classified according to the light source correlated colour temperature of daylight (red), natural (orange), white (light green) and warm white (green).

DISCUSSIONS

The eye can discriminate several wavelengths for its adjustment towards photopic, mesopic and scotopic, which is controlled by photoreceptors cones and rods (Taylor, 2000). Cones actively respond to colour because they receive three types of photoreceptor cone cells and have high-resolution ability. It is 564 nm for red, 533 nm for green and 437 nm for blue and have the highest sensitivity towards the wavelength (Wyszecki & Stiles, 1982). These three distinct values are called tristimulus values which are defined by the CIE 1931 colour space, in which they are denoted X, Y, and Z (Schanda, 2007). This trichromacy is reported to provide an accurate description of surface colour, which reflect under most lighting conditions, through non-opponent achromatic system and two opponent chromatic systems in human colour vision physiology (Lennie & D'Zmura, 1987). It is considered metameric since an endless assortment of potential SPD in the scene can produce the same colour response in the three integrated channels (Fairchild et al., 2001). Humans seem to distinguish colour differently under dissimilar lighting conditions. This study used the perceived, matched and arranged performance in F-M 100 hues to investigate the cone sensitivity performance in relation to different SPD and CCT. It was found that LED gave higher metamerism effect (less TES and less variation in mid-point caps), in which the nature of spectrum was wider within shorter to longer wavelength compared to FL and CFL. Colour confusion occurred mostly on the green to yellow range for both fluorescent lights in the study. One possible explanation is the SPD difference as difference in peak and bandwidth wavelength may cast different metamerism effect on colour discrimination performance. A previous study shared similar finding, where structured SPDs successfully increased gamut area or TES (Royer, Houser, & Wilkerson, 2012).

The subjects' mood, time to complete F-M 100 hues and cognitive task performance were previously reported to improve with increasing CCT without any significant differences found in TES between FL and LED (Hawes, Brunyé, Mahoney, Sullivan, & Aall, 2012). Similarly visual comfort, task performance and alertness were also reported to increase under daylight (CCT 6500K) (Shamsul, Sia, Ng, & Karmegan, 2013), while reduction in pupil size was found to lessen the chromatic aberration effect that might lead to enhanced colour discrimination (Berman et al., 1987). The contribution of shorter wavelength also amplified with increasing CCT compared to longer wavelength due to changes of SPD (Fotios, 2001). A study compared colour discrimination between fluorescent and LED with a range of CCT of 2618K to 2715K. The colour discrimination was reported to deteriorate under LED compared to fluorescent lighting (Royer et al., 2012). Lower total errors were found in colour discrimination for LED compared to FL and CFL in this study. The discrepancy may suggest a complex interaction between SPD and CCT when the characteristics of light shift from natural white to warm white. The finding implies that the effect of SPD pattern may over-ride the effect of CCT on colour discrimination task. However, this speculation requires further investigation to explore the interaction between SPD and CCT.

The relationship between lights (different SPD & CCT) and colour discrimination ability is important in our daily life. Fewer high-pressure sodium lamps than deluxe fluorescent lamps are installed in department stores for commodity lighting, mainly because the commodities under illumination from high-pressure sodium usually appear in dull yellow shades while the same commodities under deluxe fluorescent, at the same light level, display variation of colours. Consumer preference is prioritised instead of function accuracy (Xu, 2012) and some public areas require excellent colour discrimination. The characteristic of the light source should at least have high colour discrimination index of 80 and above to perceive actual colour, which also applies to textile premises (textile material should render the same colour as they render under the reference light) and hospital (risk of fault among medical practitioners and nurses in performing delicate colour discrimination task) (Boyce, 2014).

CONCLUSION

Different light spectrum result in different colour discrimination ability using F-M 100 Hue. The value of F-M 100 Hues to quantify the colour discrimination ability for lighting application as well as the possible complex interaction between SPD and CCT should be explored further.

ACKNOWLEDGEMENTS

REFERENCES

Aspinall, P. A. (1974). Inter-eye comparison on the 100 hue test. *Acta Ophthalmologica, 52*(3), 307–316. Retrieved from http://dx.doi.org/10.1111/j.1755-3768.1974.tb00382.x

Berman, S., Navvab, M., Martin, M. J., Sheedy, J., & Tithof, W. (2006). A comparison of traditional and high colour temperature lighting on the near acuity of elementary school children. *Lighting Research and Technology, 1*(38), 41–52.

Berman, S. M., Jewett, D. L., Bingham, L. R., Nahass, R. M., Perry, F., & Fein, G. (1987). Pupillary size differences under incandescent and high pressure sodium lamps. *Journal of the Illuminating Engineering Society, 16*(1), 3–20.

Bernecker, C. A., Davis, R. G., Webster, M. P., & Webster, J. P. (1993). Task lighting in the open office: A visual comfort perspective. *Journal of the Illuminating Engineering Society, 22*(1), 18–25. Retrieved from http://dx.doi.org/10.1080/00994480.1993.10748013

Birch, J. (2001). *Diagnosis of defective color vision* (2nd edition). London: Butterworth Heinemann.

Boyce, P., Akashi, Y., Hunter, C., & Bullough, J. (2003). The impact of spectral power distribution on the performance of an achromatic visual task. *Lighting Research and Technology, 35*(2), 141–161. Retrieved from http://dx.doi.org/10.1191/1477153503li075oa

Boyce, P. R. (2014). *Human factors in lighting* (3rd edition). CRC Press.

Boyce, P. R., & Simons, R. H. (1977). Hue discrimination and light sources. *Lighting Research and Technology, 9*(3), 125–140.

Bridger, R. S. (2003). *Introduction to ergonomics* (2nd edition). London and New York: Taylor and Francis. Retrieved from http://dx.doi.org/10.4324/9780203426135

Dalke, H., Little, J., Niemann, E., Camgoz, N., Steadman, G., Hill, S., & Stott, L. (2006). Colour and lighting in hospital design. *Optics and Laser Technology, 38*(4-6), 343-365. Retrieved from http://dx.doi.org/10.1016/j.optlastec.2005.06.040

Fairchild, M. D., Rosen, M. R., & Johnson, G. M. (2001). Spectral and metameric color imaging, *MCSL Technical Report, 2001*.

Farnsworth, D. (1943). The Farnsworth-Munsell 100-Hue and dichotomous tests for color vision. *Journal of the Optical Society of America, 33*(10), 568. Retrieved from http://dx.doi.org/10.1364/JOSA.33.000568

Farnsworth, D. (1957). The Farnsworth-Munsell 100-Hue test for the examination of color discrimination - Manual.

Faulkner, T. W., & Murphy, T. J. (1973). Lighting for difficult visual tasks. *Human Factors, 15*(2), 149–162. Retrieved from http://dx.doi.org/10.1177/001872087301500207

Fotios, S. (2001). Lamp colour properties and apparent brightness: a review. *Lighting Research and Technology, 33*(3), 163–178.

Hawes, B. K., Brunyé, T. T., Mahoney, C. R., Sullivan, J. M., & Aall, C. D. (2012). Effects of four workplace lighting technologies on perception, cognition and affective state. *International Journal of Industrial Ergonomics, 42*(1), 122–128. Retrieved from http://dx.doi.org/10.1016/j.ergon.2011.09.004

Kinnear, P. R. (1970). Proposals for scoring and assessing the 100-HUE test. *Vision Research, 10*(5), 423–433. Retrieved from http://dx.doi.org/10.1016/0042-6989(70)90123-9

Lakowski, R. (1971). The Farnsworth-Munsell 100 Hue Test*. *The Australian Journal of Optometry, 54*(10), 347–355. Retrieved from http://dx.doi.org/10.1111/j.1444-0938.1971.tb00013.x

Lennie, P., & D'Zmura, M. (1987). Mechanisms of color vision. *Critical Reviews in Neurobiology, 3*(4), 333–400.

Mann, M. (2011). The nervous system in action, Chapter 7, Vision.

Royer, M. P., Houser, K. W., & Wilkerson, A. M. (2012). Color discrimination capability under highly structured spectra, *37*(6), 441–449. Retrieved from http://dx.doi.org/10.1002/col.20702

Ryckaert, W. R., Smet, K. A. G., Roelandts, I. A. A., Van Gils, M., & Hanselaer, P. (2012). Linear LED tubes versus fluorescent lamps: An evaluation. *Energy and Buildings, 49*, 429–436. Retrieved from http://dx.doi.org/10.1016/j.enbuild.2012.02.042

Schanda, J. (2007). *Colorimetry: Understanding the CIE system.* New Jersey: John Wiley & Sons.

Schanda, J. (2015). CIE standard illuminants and sources. In R. Luo (Ed.) *Encyclopedia of Color Science and Technology* (pp. 125–129). New York: Springer. Retrieved from http://dx.doi.org/10.1007/978-3-642-27851-8_324-1

Schwartz, S. H. (2010). *Visual perception: A clinical orientation* (3rd edition). New York: McGraw-Hill. Retrieved from http://dx.doi.org/10.1036/0838594662

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, 1*(7), 159–165. Retrieved from http://dx.doi.org/10.12691/ajphr-1-7-3

SLL CIBSE. (2009). *The Society of Light and Lighting Handbook. The Society of Light and Lighting* (Vol. 44).

Taylor, A. E. F. (2000). *Illumination fundamental*. New York: Lighting Research Centre

The Society of Light and Lighting. (2012). *The SLL Code for Lighting The Society of Light and Lighting* (Vol. 44).

Verriest, G. (1963). Further studies on acquired deficiency of color discrimination. *Journal of the Optical Society of America, 53*(1), 185. Retrieved from http://dx.doi.org/10.1364/JOSA.53.000185

Wyszecki, G., & Stiles, W. S. (1982). Color science, 2nd. New York: Wiley.

Xu, H. (2012). Configuring a spectral power distribution for effective colour rendering. *Lighting Research and Technology, 44*(3), 309–315. Retrieved from http://dx.doi.org/10.1177/1477153512439447

Zahiruddin, K., Banu, S., Dharmarajan, R., & Kulothungan, V. (2010). Effect of illumination on colour vision testing with Farnsworth-Munsell 100 Hue Test: Customized colour vision booth versus room illumination, *24*(3), 159–162. Retrieved from http://dx.doi.org/10.3341/kjo.2010.24.3.159