

IMPACT OF NEW LIGHTING TECHNOLOGIES ON OFFICE ERGONOMICS

BY

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ABSTRACT

The goal of this study was to find the impact of cutting-edge light-emitting diodes (LED) lighting technologies on the office ergonomics in modern offices. An experiment was conducted in a windowless office at the University of Kansas. This experiment used four test conditions with two levels of light sources (LED and fluorescent lamps) and two levels of lighting control (with/without lighting control). A total of 30 subjects with an average age of 21.6 and eyesight of 20/20 and 20/16 participated in this experiment. Subjects performed typing tasks and color matching tasks under each one of four test conditions. Subjective evaluation of lighting quality and task satisfaction were collected using a questionnaire. High Dynamic Range (HDR) photography was used as a new approach of light measurement in offices. The results revealed that LED lighting had more consistent color rendering performance than fluorescent lighting, and also led to better typing task satisfactions. LED lighting could reduce the lighting power consumption (by up to 65.5% in this study) without any negative impact on office ergonomics. Introduction of individual lighting control could lead to better satisfaction toward the lighting quality and higher savings in lighting power consumption.

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CHAPTER 1 INTRODUCTION

1.1 Background

Lighting, ventilation and muscle soreness are the top three concerns in office ergonomics (Tiedeman J, n.d.). High quality lighting leads to a pleasant visual environment and helps achieve the highest visual performances, physical comfort and occupants' task satisfaction. Low quality lighting, on the other hand, could cause headaches, flickering sensations, itching and burning eyes, tension and visual fatigue (Tiedeman J, n.d.). Thus, lighting has a large impact on office ergonomics.

Lighting was often over-supplied in the past. Electric lighting accounts for 39% of total office electricity use (IES 2011). Most office occupants thought there was too much lighting (Bordass et al. 2001). Occupants tended to accept any lighting environment they were given, which almost immediately developed physical discomfort caused by low quality lighting (Tiedeman J n.d.). A typical method of office lighting control is using on-and-off switches for the whole lighting system, which causes a waste of electric energy without individual control of each luminaire. Therefore, individual lighting control in offices is necessary to improve the lighting efficiency and to achieve the best physical comfort.

On the other hand, artificial light sources have gone through three stages, including incandescent lamps, fluorescent/high intensity discharge (HID) lamps, and light-emitting diodes (LED). Incandescent lamps were commercialized at the end of the 19th century and are now being replaced by new light sources. Electric discharge light sources, including fluorescent and HID lamps, were brought into the market in the early 20th century and are still popular in today's lighting applications. LEDs was invented in

1962 (MIT n.d.) but only became available for illumination in the 2000s, and are now under wide applications and fast development.

The LED light sources available in the market have an efficiency of 45-80 lm/W, lamp life of more than 50,000 hours, and compatibility with advanced digital controls. Cutting-edge LED technology has a trend of replacing conventional light sources such as fluorescent lamps, which are still dominant in today's offices. The efficiency of LED fixtures in the market has exceeded that of fluorescent fixtures. The initial price of LEDs is expected to drop below that of fluorescent lamps in 2015. In addition, due to its low profile, LEDs have been used in Liquid Crystal Displays (LCD) as backlight, which will replace Cathode Ray Tube (CRT) monitors and LCD displays with fluorescent backlight. LED technology will surely affect office ergonomics.

However, simply replacing conventional light sources with LEDs does not guarantee good lighting quality. Replacing fluorescent lamps with LEDs could reduce power consumption, but may also produce glare to office workers and extra high light levels on work surfaces if the LED light sources, which are much brighter than fluorescent tubes, are not well shielded or diffused. In addition, color perception depends on the spectrum of light sources for correct color rendering. The difference in spectral power distribution between fluorescent lamps and LEDs may have potential effects on occupants' color perception. Therefore, the impact of LED technologies on office ergonomics needs to be investigated, too.

1.2 Office Lighting Standards and Recommendations

Evaluating the metrics of office lighting quality includes: ① target illuminance, ② luminance ratio, ③ correlated color temperature (CCT), ④ color rendering index (CRI), ⑤ direct and indirect glare, ⑥ light distribution, ⑦ flicker and ⑧ lighting control (IES 2004).

1.2.1 Target Illuminance

The selection of target illuminance is flexible based on the characteristics of visual tasks, the occupant's age, adaptation between spaces, and room surface conditions. In general, when visual display terminal (VDT) operation is needed in the office, the target luminance provided by general lighting should not exceed 500 lx (IES 2004). 300 – 500 lx are generally considered to be the most appropriate for VDT tasks (Ministry of Labor, Ontario, Canada 2004). 500 lx is recommended for reading tasks for users between 25 and 65 years old (IES 2011). If task lighting is used as a supplement, the general lighting can be at a lower level (IES 2004). Table 1.1 provides the determination of target illuminance categories (IES 2004).

Table 1.1 Determination of illuminance categories (source: Table 1 from IES 2004)

Category		Illuminance
Orientation and simple visual tasks:		
A	Public spaces	30 lx
B	Simple orientation for short visits	50 lx
C	Working spaces where simple visual tasks are performed	100 lx
Common visual tasks:		
D	Performance of visual tasks of high contrast and large size.	300 lx
E	Performance of visual tasks of high contrast and small size, or visual tasks of low contrast and large size	500 lx
F	Performance of visual tasks of low contrast and small size	1000 lx
Special visual tasks:		
G	Performance of visual tasks near threshold	3000 to 10000 lx

1.2.2 Luminance Ratio

High luminance ratio is necessary to provide good visibility, stimulation and attraction. However, extremely high luminance ratio will cause glare, because human visual system will have difficulties adapting a high and a low luminance level at the same time. To maintain good lighting quality without producing discomforting glare, the luminance ratios should not exceed 3:1 or 1:3 between a paper task and an adjacent VDT screen or between a task and the immediately adjacent surroundings, and 10:1 or 1:10 between a task and remote surfaces (IES 2004, 2011). To maintain visual comfort, the luminance ratios should not exceed: 1:40 between a task and luminaires, and 1:20 between a light-source-adjacent surface and a light source. To minimize VDT glare/veiling reflections, the luminance ratios between a brighter ceiling and/or wall zone and a dimmer ceiling and/or wall zone should not exceed: 4:1 in a critical situation, and 8:1 in a normal situation (IES 2011).

1.2.3 Correlated Color Temperature (CCT)

A correlated color temperature (CCT) and a color rendering index (CRI) are often used to evaluate the chromatic features of light sources. CCT describes the color appearance of the light sources. Higher CCT makes the light look cooler and lower CCT makes it look warmer. However, CCT is also related to individual preferences. Generally, a CCT lower than 3000K gives a warm perception. A CCT between 3000K and 3500K gives a neutral white perception. A CCT higher than 4100K gives a cold white perception and appears harsh and institutional in dark conditions (IES 2011). Currently there is a lack of detailed guidance or recommendation by IES on the determination of CCT,

besides the conventional Kruithof curve (Figure 1.1), which determines the ideal color temperature of electric lighting installations in an interior space. The white area represents the preferred combinations of the color temperature of a light source and illuminance. Color temperature/illuminance combinations in the lower shaded area are claimed to produce cold, drab environments, while those in the upper shaded area are believed to produce overly colorful and unnatural environments (Boyce 2003).

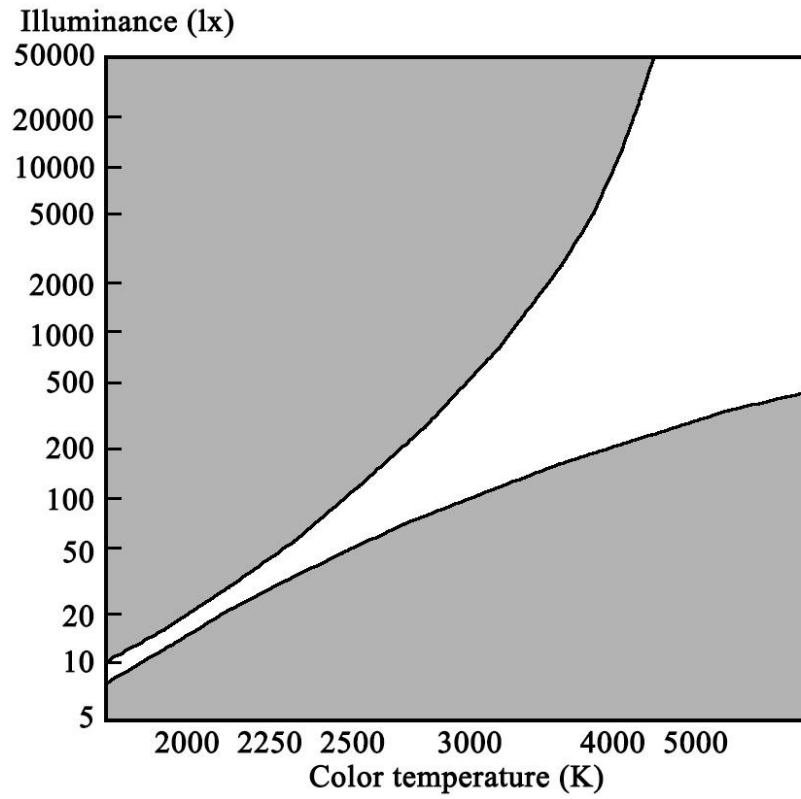


Figure 1.1 The Kruithof curve (source: Figure 7.8 from Boyce 2003)

1.2.4 Color Rendering Index (CRI)

CRI describes the ability of a light source to reproduce color appearances of various colored objects compared to natural sunlight (IES 2004). The highest value of CRI is 100. The importance of CRI depends on the extent to which color distinction is critical to the visual tasks. In general, a CRI of 70 or higher is needed to achieve visual comfort. If color-critical tasks are performed, the CRI of light sources should be 85 or higher (IES 2004, 2011).

1.2.5 Direct and Indirect Glare

Direct glare occurs when the light source is visible to the occupant's eyes. Indirect glare, which is also known as reflected glare or veiling reflection, occurs when light is reflected from a polished surface, like a visual display terminal (VDT) screen and glossy materials, and goes into the occupant's eyes (IES 2004, Occupational Health Clinics for Ontario Workers Inc. 2008). Both direct and indirect glare will reduce the visibility and cause discomfort. Direct and indirect glare can be reduced by blocking the visible light source using indirect lighting systems, or covering overhead luminaires with diffusers and lenses or dimming the general lighting with supplemental task lighting, avoiding glossy surfaces in the field of view of the office workers, and using anti-glare screens on computers (IES 2004, 2011; Occupational Health Clinics for Ontario Workers Inc. 2008; Knoll 2006).

1.2.6 Light Distribution

In most offices, shadows reduce visibility by reducing task luminance. Sharp shadows may be distracting and cause uncomfortable luminance ratio. Shadows can be softened if light reaches the task surface from various directions. Use of indirect lighting can reflect the light to a variety of directions and hence soften shadows (IES 2004).

1.2.7 Flicker

The flicker of light sources can cause headaches. Electromagnetic ballasts of fluorescent luminaires often produce flicker, together with audible hum. Most high frequency electronic ballasts can eliminate flicker and humming noise (IES 2004, 2011).

1.2.8 Lighting Control

Individual dimming control tailors the illuminance, luminance and their ratios to help the lighting system to accommodate different uses, moods and populations. Office occupants can use the individual lighting control to adjust the lighting condition to fit the needs of their various tasks and their individual preferences. Lighting control can also cut the energy use of electric lights (IES 2004, 2011).

1.3 Objectives and Research Scope

The purpose of this study was to find the impact of cutting-edge LED lighting technologies on office ergonomics in modern offices, and to provide guidelines on future office lighting designs and the preferences of office users.

To look into the impact of LED technologies on office ergonomics, the scope of this study covered the effect of LED lighting and its digital controllability on office tasks, and occupants' evaluation of lighting quality and task satisfaction, which were commonly examined in office lighting studies. Subjective evaluation of the working environment and subjects' moods directly related to interior color and arrangement of the office other than lighting quality were not examined, as they are highly dependent on individual preferences.

This experiment was used to achieve specific objectives, as follows:

- To examine whether LED has an impact on typing task performance,
- To examine whether LED has an impact on color perception,
- To examine whether LED has an impact on task satisfaction,
- To examine whether LED has an impact on office occupants' attitudes toward the lighting quality,
- To examine whether introducing individual lighting control alters any impacts discovered above.

For comparison, fluorescent luminaires, which are dominant in today's office lighting applications, were tested together with the LED technologies. Subjects performed office tasks using materials presented on both hardcopies and on the VDT screen under four test conditions:

- LED lighting without lighting control,
- LED lighting with lighting control,
- Fluorescent lighting without lighting control, and
- Fluorescent lighting with lighting control.

The subjects' task performances, lighting quality evaluation and task satisfactions were then measured in the experiment to identify those aspects on which the LED lighting technologies had impacts.

Outcomes and findings obtained in this study are expected to guide the applications of LED technologies in modern offices for the benefit of future developments in office ergonomics.

CHAPTER 2 LITERATURE REVIEW

2.1 Visual performance in office

Visual perception obtains the majority of the information necessary to carry out daily office tasks. Therefore, a review of the visual perception theories and fundamentals are extremely important to understand and facilitate this study.

There are two types of photoreceptors that contribute to vision: cones and rods. There are three different types of cones (S-cone, M-cone, and L-cone) but only one type of rod. All the rod photoreceptors contain the same photo pigment and hence have the same spectral sensitivity. Each type of cone has different photo pigments and thus has unique spectral sensitivity. Different spectral sensitivities make cones able to discriminate differences in wavelength, thus achieving color vision. Since all rods have the same spectral sensitivity, they are unable to detect wavelength differences. Color vision is contributed by cones only (Boyce 2003).

Rods and cones also have different sensitivity to retinal illuminance. Rods are much more active under low light levels than are cones. While under high light levels, cones are more activated than rods. Light levels can be sorted into three stages based on the combination of activated photoreceptors, also as shown in Figure 2.1.

- Photopic vision, typically seen in offices, where the adaptation luminance is higher than 3 cd/m^2 . Cones are dominant under photopic vision.
- Mesopic vision, not common in offices, where the adaptation luminance is between $0.001 - 3 \text{ cd/m}^2$. Both cones and rods are active.
- Scotopic vision, merely seen in offices, where the adaptation luminance is lower than 0.001 cd/m^2 . Rods are dominant under scotopic vision.

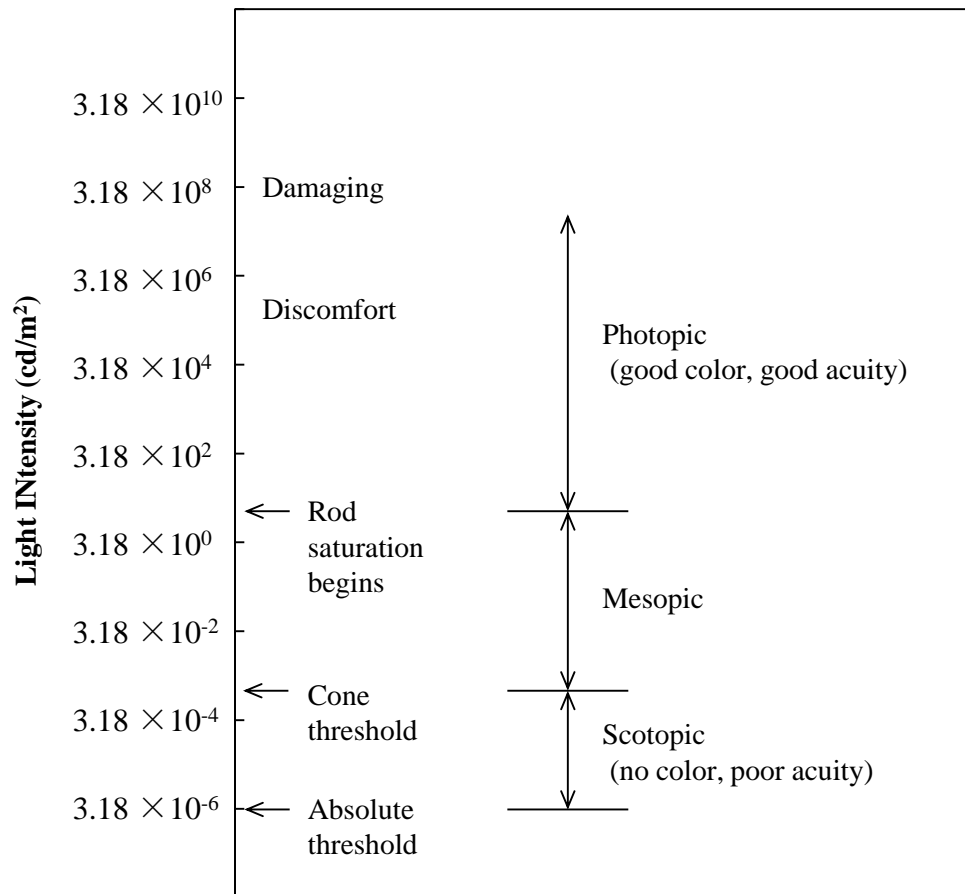


Figure 2.1 The range of light intensities that confront the human eye (figure 1 from Boff 1988)

The distribution of rods and cones is shown in Figure 2.2. Cones were highly concentrated in the fovea, the center of the retina. Beyond the fovea, the density of cones dropped sharply and achieved a very thin uniform distribution across the rest of the retina. No rods were presented in fovea. The cone system is more sensitive at photopic light levels while the rod system is more sensitive at scotopic light levels. This means under photopic light levels such as a typical office lighting condition, where the adaptation luminance is higher than 3cd/m^2 , the cone system is dominant in visual perception over the rod system. The high density of cones in the fovea results in fine resolution and color vision in this area of the retina (Boyce 2003, Boff 1986). If the tasks fall in the central fovea on the retina, best visual acuity and color vision could be achieved.

In order to maintain the best visual acuity and color perception, the light level in the office should be kept within photopic vision. Since fovea is dominant under photopic vision, the tasks should be kept in the central area of the visual field in order to make sure that the retinal images of tasks fall in the fovea.

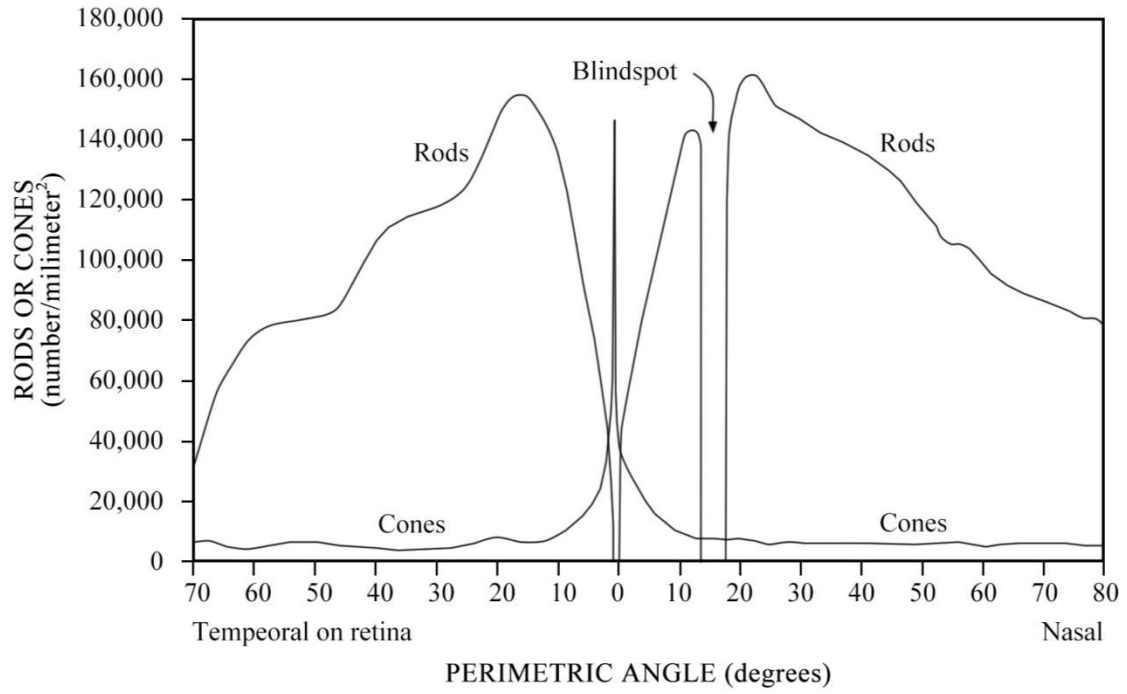


Figure 2.2 The distribution of rod and cone photoreceptors across the retina
 (source: Figure 5.3 from Boff 1986)

Aberrations and imperfections of human eyes also affect visual performance. One is the aging effect on visual acuity. As shown in Figure 2.3, visual acuity increases in the early ages and peaks in the twenties, then declines sharply in later life.

Another imperfection of the human eye is the abnormal color vision, which includes anomalous trichromatopsia, achromatopsia, and dichromatopsia. The majority of people who have abnormal color vision are anomalous trichromats. Anomalous trichromats can present the color vision as trichromats, but their coefficient curves are different shapes and the color vision differs from the normal one. An extremely small number of people are monochromats. Monochromats have no more color vision. They are able to match lights by adjusting the intensities only. Dichromats can match any light with a mixture of two primary lights (Pirenne, 1967).

To achieve the best visual performance, subjects participating in the experiments should be in their twenties, when they have the best visual acuity in their life. What's more, to avoid the influence of abnormal color vision on color perception, subjects must have normal color vision.

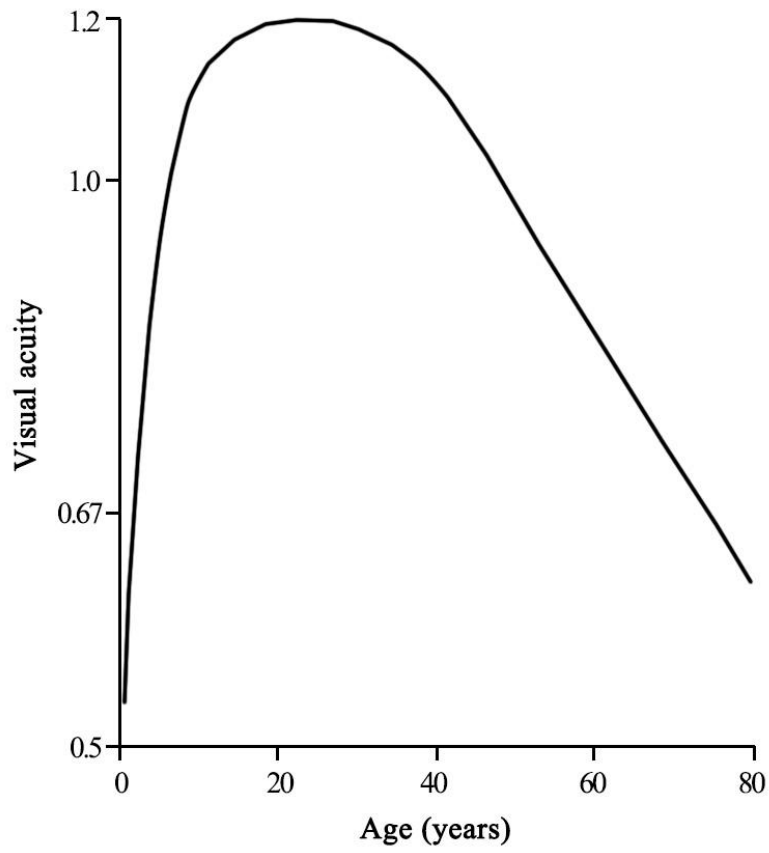


Figure 2.3 A representation of the age-related variation of visual acuity (source: Figure 5.1 from Weale, 1992)

The human eye can see a wide range of illumination levels of about 10 – 12 log units, but the optic nerve's response range is quite limited (perhaps 100:1) (Tovee 1996). To cope with this problem, the visual system employs a strategy of adaptation. The process of adaptation includes change in pupil size, neural adaptation and photochemical adaptation. When exposed to a new lighting condition, the iris constricts or dilates to decrease or increase the levels of retinal illumination. This is a relatively fast process. It takes about 0.3s for iris constriction and about 1.5s for iris dilation. Neural adaptation is the change in neural sensitivity produced by synaptic interactions in the retina. This process is even faster, less than 200ms. This explains why it is possible to look around most lit interiors without being conscious of adaptation. Photochemical adaptation is the longest process. Retinal photoreceptors contain pigments. When absorbing light, the pigments break down. Under dark conditions, the pigments are regenerated. The sensitivity of photoreceptors was largely a function of the percentage of the unbleached pigment it contains (Boyce 2003).

There are some typical quantities about the adaptation time. In addition, dark adaptation usually requires a very long time (30 minutes or so) while light adaptation is usually completed in 3 – 5 minutes (Boyce 2003). Exactly how long it takes to adapt to a change in retinal illumination depends on the magnitude of the change. If the change of retinal illumination is within 2 – 3 log units, neural adaptation is sufficient and will be completed in less than one second. If larger changes happen, photochemical adaptation is necessary. But if the change is still within the range of photopic vision, the adaptation will be completed within a few minutes (Boyce 2003). What's more, (Boff et al 1988) revealed the concrete courses of light adaptation as shown in Figure 2.4. For the foveal

adaptation, sensitivity increases rapidly (threshold drops) during the first 3s and then levels off. After 100s the sensitivity remained almost constant. If the light level changes beyond the range of photopic vision, the adaptation time will be much longer.

In the experiment, whenever subjects were exposed to a new lighting condition, they had to be given sufficient time for the process of adaptation.

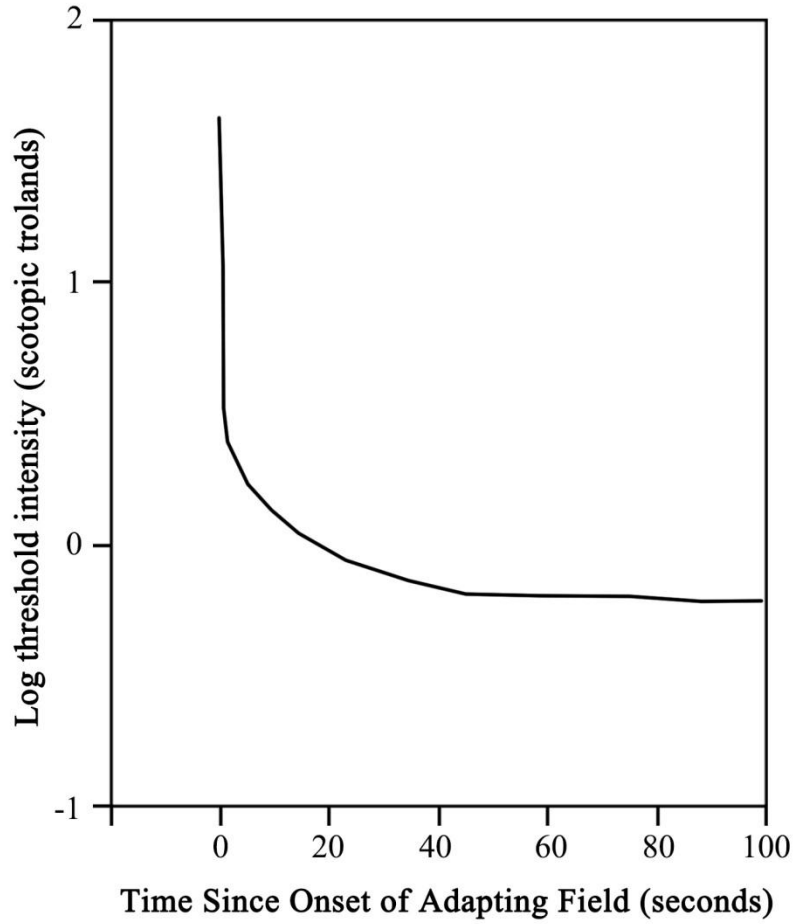


Figure 2.4 Increment in intensity required to detect a test light superimposed on an adapting background as a function of time since onset of adapting field for foveal vision (Boff 1988)

Moreover, external factors also have effects on human visual performance. According to previous research, lighting conditions have effects on color perception. It was found in the Hunt effect (Hunt 1952) that the saturation of colors gradually decreased as the adapting light intensity was lowered. Colored objects' hues also shifted with changes in luminance, which is known as the Bezold-Brucke effect (Davis & Ohno, 2009). Davis and Ohno (2009) also found that colored objects appeared markedly different under different illuminance levels in typical color rendering situations, which was consistent with the Hunt and Bezold-Brucke effects.

To avoid the color shifts caused by light levels, when testing color perception, the illuminance levels on different colored objects must be kept the same.

2.2 Previous research on office ergonomics and lighting

2.2.1 Research studies on office lighting quality

Previous research concerning lighting and office ergonomics focused on the effect of lighting quality on office occupants' task performances, moods and task satisfactions. Veitch and Newsham (1998) tested nine different lighting conditions, including the combination of three lighting power densities and three Designers' Lighting Qualities: Recessed troffer with prismatic lens (low quality), recessed troffer with parabolic louver (medium quality), and indirect or direct/indirect luminaires (high quality). The Designers' Lighting Qualities were validated by North American lighting designers in a survey. Subjects were asked to work for a whole day with various paper- and computer-based office tasks under each lighting condition. The results showed that when the lighting power density declined, the performance, satisfaction and mood of subjects didn't show a

clear decrease. Which means energy-efficient lighting and high-quality lighting could be compatible. However, this study didn't take LED into consideration. Despite of Designers' Lighting Qualities and lighting power densities, other photometric factors, like light distribution, CCT, CRI, illuminance, luminance contrast etc., were not examined in the experiments.

Later, Veitch and Newsham (2000a, 2000b) compared the work performance of office workers and the workers' preference of office luminous conditions. Those office workers were given lighting control before or after office tasks. The experiments were conducted in a windowless open-plan office. The lighting system contained continuously dimmable general lighting, and on-and-off controlled task lighting. Subjects were divided into two groups: choose-session (CS) participants and post-session-preferred (PP) participants. CS participants were given choices of various workspace lighting conditions before office tasks. PP participants had no choice but to work under lighting conditions that CS participants had chosen, and were allowed to choose the lighting condition after office tasks. It was found that although the CS participants were given lighting control, there were no differences in satisfaction or performance. PP participants' lighting choices had less VDT glare and closer to current lighting and energy codes than CS choices. The authors also indicated that having experience with the working environment could lead to a better ability to achieve a comfortable lighting condition when lighting control was available. Participants, who made lighting choices at the end of a working day, chose conditions that created less VDT-screen glare, as compared to those who chose lighting conditions at the start of the day. In this study, only an on-and-off switch was provided to control the task lighting. Subjects might not have been able to find the preferred task light

level. Besides, the light sources used in the study were fluorescent lamps, which had constrained dimming controllability. The common problem of dimming fluorescent lighting, such as flickers and humming noises, were not evaluated.

The lack of experience in lighting environment can also be found in other studies. Veitch and Gifford (1996) carried out a study on perception and performance under different lighting conditions. Three lighting conditions were provided: one with general lighting only, another with general lighting and incandescent task lighting, the third with general lighting and CFL (compact fluorescent lamp) task lighting. Subjects were divided into two groups. One group chose their most preferred lighting condition, while the other group had no choice but to work under assigned lighting conditions. Subjects were asked to perform a series of cognitive and creative tasks and rate their mood. It was found that subjects who were given a choice actually had poorer and slower performances on creative tasks than those with no choice. In addition, it was found that the mood and cognitive task performance were not associated with lighting condition preferences. Light sources used in this study were fluorescent and incandescent, LEDs were not yet involved.

Boyce et al. (2003, 2006a) developed an experiment to test the effect of different forms of office lighting on the performance, health and well-being of office workers. Four lighting conditions were tested. The first one was a regular louvered general lighting; the second one was direct/indirect general lighting with wall washers; the third one was direct/indirect general lighting with wall washers and three-way-dimming task lighting; and the last one was suspended direct/indirect general lighting with dimmable direct component, and non-dimmable wall washers. Subjects performed various tasks under

each lighting condition for a whole day. The results showed that complex cognitive tasks showed no simple effects of lighting design. However, when given lighting control, subjects showed more sustained motivation and the highest ratings toward the lighting design. Subjects also considered the direct/indirect lighting systems to be more comfortable than direct-only systems. However, in this study subjects were not given full control of all luminaires. They were given only three-way control to the task lighting, and continuous dimming control to the direct part of the direct/indirect luminaire. The controllability of the lighting was constrained.

Veitch et al. (2007, 2008) examined office occupants' appraisal, task performance and well-being. Each subject worked under only one of six different lighting conditions for a whole day. The system setup and simulated office tasks were similar to those adopted by Boyce et al. (2003, 2006a). It was found that people who considered the office lighting as having higher quality also rated the space as more attractive, reported a more pleasant mood, and showed greater well-being at the end of the day. Direct–indirect lighting and individual control were favored by the subjects. Lighting conditions that improved visibility also improved the task performance.

Eklund et al. (2000) tested the influence of lighting quality on office task performance. Three lighting conditions with close surface illuminance were tested in three identical test rooms. The first one was regular array of recessed general lighting, which was considered to have moderate lighting quality. The second one was suspended direct/indirect general lighting with adjustable task lighting, which was considered to have high lighting quality. The third one was a single recessed luminaire, which was considered to have poor lighting quality. Subjects performed data entry tasks and various

cognitive tasks, and rated their mood, alertness and subjective impressions of the environment. It was found that different lighting conditions had no effect on the sustained performance of the data entry task or on the mood and alertness of the subjects. Although this study focused on the influence of lighting quality, lighting control was not provided, which was also considered as an important factor of lighting quality. The effect of lighting control on occupants' mood and satisfaction was not taken into account. Again, LED light sources were not involved.

Boyce et al. (2000) looked into the effect of individual lighting control on task performance, mood and illuminance. Three lighting conditions were tested in three identical offices with identical luminaires. In office 1, lighting control was provided in an illuminance range of 12 - 1240 lx. In office 2, lighting control with an illuminance range of 7 – 680 lx was provided. In office 3, the illuminance on working surfaces was fixed 490 lx without lighting control. Subjects conducted proofreading tasks under different lighting conditions. It was found that although access to lighting control is desirable, and made the tasks seem less difficult and saved energy, it didn't result in more positive mood, like more alertness. There was no proven effect of lighting control on the task performance either. Newsham et al. (2004) also studied the effect of dimming control on office occupants' satisfaction and task performance. Four lighting layouts were tested: (1) recessed general lighting only, (2) recessed general lighting with partition washer, (3) recessed general lighting with angle-arm task light, (4) direct/indirect lighting with angle-arm task light. Down lights along the corridor were provided for each lighting layout. Subjects worked for a whole day under one of four lighting conditions. Lighting control was not provided until the latter half of the afternoon. It was found that after lighting

control was provided, there were significant improvements in mood, room appraisal, satisfaction, self-rated productivity and visual discomfort. The authors also indicated that exercising control to achieve a preferred condition was more effective on satisfaction than lighting control itself. Task performance was believed not affected by lighting control. Light sources used in this study were fluorescent lamps. The effect of LED was still unknown.

Baron et al. (1992) tested the effect of illuminance and spectral power distribution on office task performances. Subjects performed various tasks under $2 \times 4 = 8$ lighting conditions with two levels of illuminance (approximately 150 lux and 1500 lux on the desk surface) and four lamp CCTs (3000K, 3600K, 4200K, 5000K). It was found that subjects reading profiles of employees under lower illuminance level tended to have higher appraisals toward the employees. Subjects exposed to lower CCT preferred to resolve interpersonal conflicts through collaboration rather than resolving conflicts through avoidance. Subjects exposed to lower CCT were also willing to donate longer time as volunteers. Subjects exposed to lower CCT and lower illuminance had much higher self-set goals that they wanted to complete. This study only focused on two aspects of lighting quality, illuminance and CCT. Other factors, such as lighting control and color rendering, were not included.

2.2.2 Office tasks used in previous studies

Three parameters have commonly been taken into consideration in office ergonomic studies: performance, satisfaction and physical comfort. Various office tasks were used to evaluate occupants' task performance. Generally two types were most

common: proofreading and typing. Although many other tasks were designed such as conveyor belt tasks (Boyce et al.2006), video games (Veitch & Newsham 1998), word puzzles (Akashi & Neches 2005), interviews (Shikakura & Morikawa 2003), domino matrixes,(Sheedy et al 2005) etc., proofreading and typing represented the most typical office work in the real situation.

Veith and Newsham (Veitch & Newsham 1998, 2000a, Newsham & Veitch 2001) designed an experiment to use proofreading tests to examine the effect of lighting quality on task performance. Two strings of text were presented on the screen. Subjects were asked to mark the differences between two strings. The speed and accuracy were recorded for task performance evaluation. The results showed that when the lighting power density declined, the task performance didn't show a clear decrease.

Kwallek et al. (2007) used two types of proofreading tasks, a zip code proofreading task and a text proofreading task, to test the effect of interior colors on work week productivity. In the zip code proofreading task, subjects were required to check a zip code list against an original list for errors. The list was longer than they could finish. The text proof reading task required subjects to check manuscripts against original ones for errors. They were not only asked to identify the errors but also to correct them. Both the zip code proofreading task and the text proofreading task were conducted within an allotted time limit. It was found that the influence of interior colors on productivity depended on the subjects' stimulus screening ability and time of exposure to interior colors.

Buchner and Baumgartner (2007) used a proofreading task to test if text-background polarity (dark text on light background, or light text on dark background)

affects performance. Text materials were presented on a TFT monitor. There were various types of spelling errors in the text. Subjects were asked to find and mark as many errors as they could by double-clicking the word. The task was first conducted without time limit and then repeated with time limit. It was found that task performance with positive polarity (dark text on light background) was clearly better.

For typing tasks, Veitch and Newsham (1998) designed a computerized typing task. A model text was presented in a window on the top of the screen. Subjects were required to retype the model text into a window on the bottom of the screen. The computer beeped when an error happened. Subjects could not continue until the error was corrected. Therefore the accuracy of the typing task was fixed to 100%, only typing speed was measured. Later Veitch and Newsham (Veitch & Newsham 2000a, 2000b, Newsham & Veitch 2001) used typing tasks in their studies but the accuracy was not fixed. Both speed and accuracy were measured. The typing speed was measured as characters per second.

Boyce et al. (Boyce et al. 2003, 2006a, Veitch et al. 2007, 2008) used a typing task to evaluate task performance. The subject was given a binder of typing materials consisting of 200-300 words, one paragraph on each page. The subject was asked to fix the pages on a document holder and type the paragraph into the computer using the NRC Typing Task software (Boyce et al. 2003, 2006a). Words on different pages were in different print sizes, which created a difference in visibility and thus provided an index of sensitivity for this task. Accuracy and typing speed were recorded to score the task performance.

Kwallek et al. (2007) assigned a typing task to subjects. Subjects were asked to type English text. The text was longer than anyone could finish. The time was fixed. Task performance was scored according to the accuracy.

2.2.3 Subjective evaluation using questionnaires

Although office tasks are useful to reflect the lighting effect on task performance, they cannot be used to reveal the subjects' satisfaction and physical comfort toward the lighting environment. Therefore, to make up for that, questionnaires were used in the literature to evaluate satisfaction and physical comfort. Veitch and Newsham (1998) asked subjects to rate their mood, satisfaction, physical comfort and aesthetic impression of the room, also on a 0 - 8 scale. In later studies conducted by Veitch and Newsham (Veitch & Newsham 2000a, 2000b, Newsham & Veitch 2001), subjects also rated the task difficulty and their productivity, their mood, and their satisfaction towards the work environment and workspace lighting. Newsham et al. (2004) asked subjects to rate their pleasure, arousal and dominance factors on an 8-point scale, the room appraisal on a 0 – 100 scale, the workplace satisfaction on 4-point scale, lighting control quality on a 5-point scale, and two-choice lighting preferences (preferred or not). The authors also gave subjects open-ended questions of some marginal factors. Veitch and Gifford (1996) used three questionnaires to rate subjects' self-efficacy, mood and perceived control in the working environment. Moore et al. (2004) also used questionnaires to evaluate user attitudes toward lighting control and lighting condition among 14 office buildings in the UK. Boyce et al. (2000) used questionnaires to evaluate subjects' mood, alertness, task difficulty, impressions of the working environment and attitudes toward lighting quality.

Boyce et al. (2003) used a questionnaire to collect subjects' rating of the appraisal of lighting, preferences of the appearance of the office, mood, task competence, satisfaction with the environment and performance, visual and physical discomfort, and difficulty of the tasks. Subjects were also asked to finish a survey concerning lighting control. In a study conducted by Sheedy et al. (2005) concerning visual effects of the luminance surrounding a computer screen, after conducting office tasks, subjects rated symptoms including pulling, burning, ache, strain, irritation and pain on a 0-100 scale. Buchner and Baumgartner (2007) used questionnaires to assess subjects' mood and fatigue after the task. All these studies have supported the use of questionnaires in this study on LED lighting technologies on office ergonomics.

2.3 Research Gap

There is a research gap consisting of three issues not addressed in previous studies, as follows.

- Fluorescent lamps were the only light sources investigated in previous studies, which are still dominant in office lighting applications. As a result, the outcomes and findings obtained in previous studies based on fluorescent lighting cannot be directly applied in modern offices using LED lighting technologies. As mentioned above, LEDs differ from fluorescent lamps in many photometric aspects, such as spectral power distribution, color rendering performance, surface luminance, digital controllability, etc. Whether LED lighting technologies have similar or different implications on office

occupants' work performance, color perception, and satisfaction is still unknown.

- According to previous studies, lighting control was highly desirable and had significant effect on occupants' mood and satisfaction. The importance of lighting control is obvious. In some previous studies (Veitch and Newsham 2000a, 2000b, Veitch and Gifford 1996, Boyce et al. 2000, 2003, 2006a, Veitch et al. 2007, 2008, Newsham et al. 2004), individual lighting control was provided to subjects. However, in most studies, only limited controls such as step dimming and on-and-off control were available, especially for task lighting. Continuous dimming over a wide range of light output to the entire lighting system, which is widely deployed in LED technologies today, was seldom used in previous studies. One possible cause is the constrained controllability of fluorescent lamps. Therefore, it is necessary to test the continuous and smooth lighting control over a wide range, and find out to which extent the lighting control affected office ergonomics.
- In addition, the simulated office tasks used in previous research were mainly simple cognitive tasks, such as typing and proof reading. Although these tasks well represented the most common office works in the real VDT offices, they cannot be used to measure the color perception of office occupants as they are usually presented in black and white or gray scale. An office task concerning color perception needs to be developed. It is also necessary to test the color rendering performance of LEDs used in modern offices as LEDs have different spectral power distributions from fluorescent and incandescent lamps.

To bridge this gap and address those research issues, this study focused on the effect of LED on modern office ergonomics by comparing that to the conventional fluorescent lighting. A total of $2 \times 2 = 4$ lighting conditions were tested, consisting of two levels of light source (LED and fluorescent) and two levels of lighting control (with or without). Subjects performed office tasks under four test conditions:

- LED lighting without lighting control,
- LED lighting with lighting control,
- Fluorescent lighting without lighting control, and
- Fluorescent lighting with lighting control.

CHAPTER 3 METHODOLOGY

To address those three research gap issues, the following methods were carried out in this study to compare the impact of LED technologies with that of fluorescent lamps on office ergonomics.

- A survey on current office lighting was conducted to find typical office lighting conditions. The lighting systems in the test room were constructed based on the results of an office lighting survey.
- Thirty subjects with normal visual acuity and color vision were recruited. A 2 × 2 within-subjects design was used. Four lighting conditions were tested with two levels of light sources (LED/fluorescent) and two levels of lighting control (with/without lighting control). The same group of subjects performed office tasks under all four test conditions.
- Office tasks performed were a typing task and a color matching task.
- A questionnaire was used to evaluate subjects' attitudes toward lighting quality and task satisfaction.
- The high dynamic range (HDR) photography was introduced as a new method of non-uniform light measurement with extraordinary high resolution. The HDR photography deploys a digital camera to capture the spatial luminance values across an entire scene at pixel level within 1~2 minutes. The HDR photography has been proven reliable for luminance mapping with acceptable accuracy by Cai and Chung (2011) and Inanici (2006). It has average errors of 2.8% for luminance mapping gray surfaces, 1.5% for black surfaces, 10.1% for color surfaces, and 6.6% for light-emitting surfaces Cai and Chung (2011),

or 7.3% for all, 5.8% for grayscale targets and 9.3% for color targets Inanici (2006). The HDR photography was used for office lighting measurement in this study with fast speed, high resolution and high accuracy.

They are described in more detail below.

3.1 Survey on Current Office Lighting Conditions

To find the typical lighting strategies and layout in modern offices, the field survey was carried out in 21 offices at the University of Kansas in Lawrence, Kansas. This survey collected data of lighting fixture types, mounting methods, lamp types, CCT, VDT types, quantities and screen sizes, and lighting control methods. A literature review was also conducted to find the office lighting settings used in previous studies available in the literature.

Figure 3.1 shows some example photos taken in some of the surveyed offices.

This field survey was designed to obtain the following data:

- The type, quantity and mounting method of lighting fixtures and lighting control devices in an office.
- Illuminance values and CCTs at desk surface (0.75m above the ground).
- The quantity and size of displays in the office.
- A sketch of the plan view of the office and lighting fixture layout.
- Field photos of the ceiling, floor, walls, luminaires and lighting control devices taken using a Canon T2i digital camera fitted with a Sigma 10mm fisheye lens.



(a)



(b)



(c)



(d)



(e)



(f)

Figure 3.1 Office lighting survey field photos. (a) and (b): private offices of faculty and staff, (c) and (d): non-private offices of staff, (e) and (f): graduate students' offices.

In addition, to search for typical lighting layouts, the following office lighting studies conducted in the past decade were reviewed: Veitch and Newsham 2000a, 2000b, Newsham and Veitch 2001, Veitch and Newsham 2010, Boyce et al, 2003, 2006a, 2006b, Mills et al. 2007 .

After summarizing all 32 cases either investigated in the field or obtained from the literature, detailed results are shown in Table 3.1. The percentage of each item was calculated by the frequency of the presence of the interested item divided by the total number of cases.

Table 3.1 Office lighting layout statistics

Type of items			
(percentage of presence in all cases)			
General lighting			
Fixture type	prismatic lensed (40.6%)	direct/indirect (25.0%)	parabolic louvered (15.6%)
	indirect (9.38%)	parabolic lensed (9.38%)	louvered (6.25%)
Mounting method	ceiling recessed (53.1%)	surface mounted (28.1%)	ceiling suspended (18.8%)
	partition mounted (6.25%)		
Lighting control	on-and-off only (68.8%)	continuous dimming (15.6%)	occupancy sensor (12.5%)
	N/A (3.13%)		
Light source	fluorescent T8 linear (71.9%)	fluorescent T5 linear (12.5%)	N/A (15.6%)
Task lighting			
Mounting method	under-shelf (6.25%)	desktop (6.25%)	N/A (87.5%)
Lighting control	switch (6.25%)	step dimming (6.25%)	N/A (87.5%)
Light source	Fluorescent (12.5%)	N/A (87.5%)	

It is found that the most common general lighting in offices is ceiling recessed fixtures with prismatic lenses. Linear fluorescent T8 lamp is the most widely used light source. An on-and-off switch is the typical lighting control method.

Among the 32 office lighting cases, only four provided task lighting, most of these task lightings were under-shelf mounted.

The average horizontal illuminance at 30 inches (0.75m) high above the floor is 503.7 lx, with a standard deviation of 156.2 lx. The average CCT is 3639.0 K, with a standard deviation of 892.9 K. The average quantity of the displays is 1.38 per office, and the average size of the displays is 19". In the field survey, the CRI of light sources were difficult to collect due to limited access to the actual light sources sealed in the luminaire. However, in a literature survey there was a trend of CRI increase, from 80 in the early 2000s to 85 in the most recent studies.

3.2 Subject Recruitment

A total of 30 subjects participated in this study. They were recruited on the campus of the University of Kansas in Lawrence, Kansas. To avoid aging effect on human visual performances, subjects were required to be 18 – 29 years old (obtained by checking the figure 2.3, above, when the visual acuity reaches the highest level). Upon arrival, subjects were screened by self-reporting their age and by reading Snellen eye charts pasted on the back wall of the test room, as shown in Figure 3.2. When reading the eye charts, subjects stood against the wall opposite the eye charts. The distance from the subjects' eyes to the eye chart was 11'-4" (3.45m). The letters on the eye charts were chosen from the following 12 letters: C, D, E, F, H, K, N, P, R, U, V, Z, and were

presented in san-serif font (BSI 2003). The eye charts were developed according to British standards BS 4274-L: 2003 (BSI 2003). Only those subjects with eyesight of 20/20 or higher (20/20, 20/16, 20/12.5) were qualified for the experiment. The eye sight of 20/20 is the average eyesight of human beings. Subjects with eye sights lower than 20/20 could feel difficult to see typing materials clearly and could easily have visual fatigue.



Figure 3.2 Snellen eye charts

Subjects were also required to have normal color vision to prevent any errors introduced by abnormal color perception. Upon arrival, subjects were asked to self-declare if they have abnormal color vision. In addition, subjects needed normal audio acuity to detect sound alerts given by computer as a reminder of any typing errors in the typing task. In the test room, which was a relatively quiet and private office, subjects were given verbal introductions to the experiment and were asked to respond if they understood or had any questions, in order to test if they had normal audio acuity.

In summary, among the 30 qualified subjects, 19 were female and 11 were male. All subjects were 18 – 29 years old, with an average age of 21.6 and standard deviation of 3.29. All subjects had an eyesight of 20/20 or 20/16, normal color vision and normal audio acuity.

3.3 Questionnaire

In addition to the photometric measurements and assessments of office task performances, a supplemental questionnaire was developed to better illustrate subjects' attitude toward lighting quality and task satisfaction. The questionnaire contains three sections. A complete list of the questions is shown in the Appendix.

The first section is an office lighting quality survey, developed based on the work of Eklund and Boyce (1996). There are a total of 17 questions in this section, covering evaluation of lighting level, light distribution, glare, color rendering, CCT, noise, flicker and overall impression.

In the office lighting quality survey, all questions are close-ended questions with only two options: agree or disagree. Close-ended questions are suitable for asking many

questions in a short period of time, and assessing learning or attitudes when issues are clear (IAR 2007).

Also, in a pilot study it was found that most subjects lacked moderate knowledge of office lighting. For example, when asked to dim the luminaires, many subjects were not well experienced in finding the light level they preferred the most. Most subjects did not have any experience of extreme lighting conditions in offices, such as severe glare or extremely non-uniform light distribution. Thus, the questionnaire is intended to be as simple as possible. If complicated questions were given, subjects might have difficulties in precisely describing the lighting quality or the problems they met. Thus if given scaled questions, their ratings might not be accurate and might introduce more errors.

The second section contains subjective ratings of office task difficulties and satisfaction with task performances, also on a 0 – 4 semantic scale. Detailed information of the scales was shown in the Appendix.

The questionnaire was given right after the subjects finished all the office tasks at one session under a certain test condition. The questionnaire was presented on the computer screen. Subjects were asked to click on the answers with the mouse.

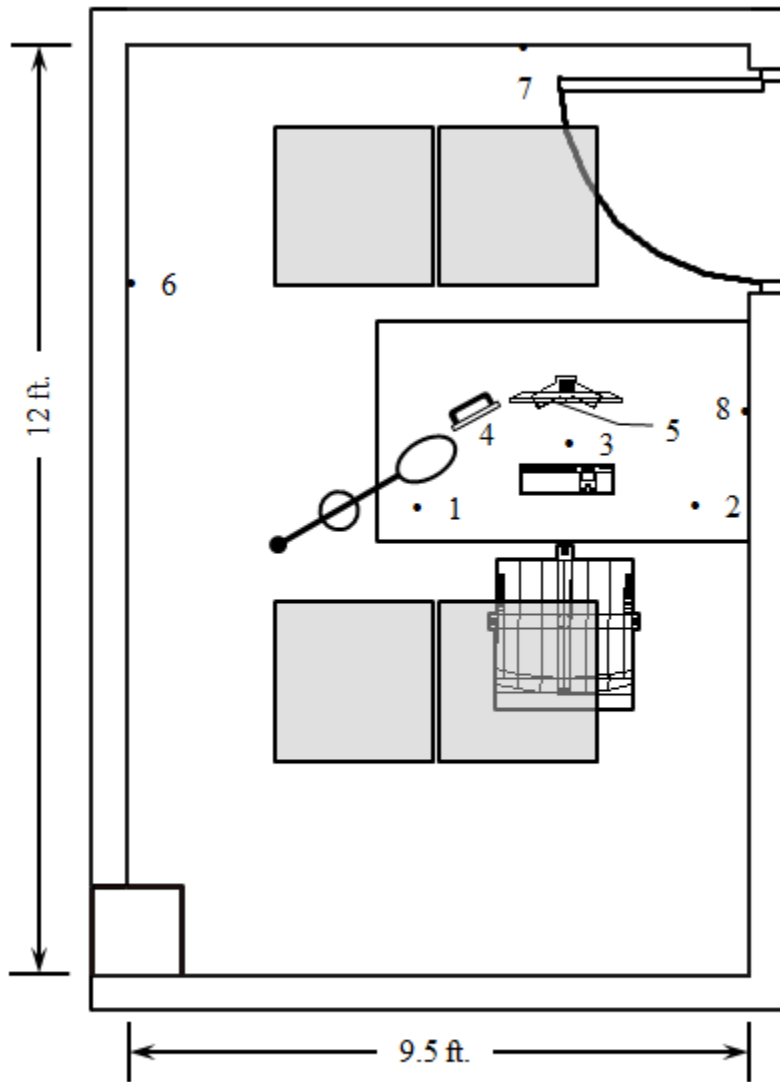
3.4 Experiment

3.4.1 Experiment Setup

3.4.1.1 Test Room Setup

The experiment was conducted in a windowless office (2135A Learned Hall) with suspended ceiling at the University of Kansas. A windowless office was chosen to

eliminate any fluctuations of natural daylight. A plan view and a fish-eye view of the test room are shown in Figures 3.3 and 3.4. The dimensions of the test room are 9'-6" (2.90m) wide, 12' (3.66m) deep and 9'-5" (2.87m) high. A 60" (1.52m) × 30" (0.76m) office desk was put in the office, together with an adjustable office chair, placed close to the entrance wall. As shown in Figure 3.2, seven points were carefully selected for photometric measurements, including illuminance, CCT, and luminance. Points 1 – 3 were on the desk surface. Point 4 was on the center of document holder. Point 5 was on the screen. Points 6 – 8 were on the walls, 4 ft. above the ground, which is close to the eye level of the sitting office occupants. The sample points were marked with small pieces of white print paper. Print paper has diffusive surfaces, thus it has uniform luminance on the surface and does not cause glare. The locations of sample points are shown in Figure 3.3.



■ Ceiling luminaires

1 ~ 8: Sample points

Figure 3.3 Plan view of the test room



Figure 3.4 Fisheye view of the test room

On the desk there were a Dell 23" LCD display with LED backlight, a keyboard, a mouse, a pair of speakers, and a document holder. Although in the office lighting survey it was found that the average size of VDT was 19", there was a trend that the size of the office VDT grew bigger than 22". Due to the limited space on the desktop, most typical office LCD displays in the market are smaller than 24". Therefore, a 23" display was selected. The display has built-in anti-reflection coating on the screen which reduces VDT glare. A specially-designed chin rest was mounted on the edge of the desk, in front of the chair, to fix the position of subjects' heads during the experiment (Figure 3.5). A desktop PC was placed under the desk to run office task programs. A camcorder was mounted behind the subjects to record the process of the experiments.

A document holder put next to the screen on the left of the computer display was used to attach materials of office tasks, as shown in Figure 3.4, above. A properly positioned document holder can reduce eye motion and discomfort, and help subjects maintain a proper neck posture, hence to prevent eye and neck strain. (Knoll 2006) As discussed in chapter 2.1, under typical office lighting conditions, central fovea reaches highest visual acuity and color vision. Using a document holder helps the image of typing materials fall in the central fovea, and thus helps subjects achieve their best visual performance.



Figure 3.5 A chin rest to fix the positions of subjects' heads

3.4.1.2 Lighting Systems Layout

Two lighting systems were installed in the test office successively. Firstly an LED lighting system, and then a fluorescent lighting system. Although different in light sources, these two lighting systems should otherwise be identical in terms of physical look, layout, and photometric performance. The lighting layouts in the test room were designed to represent the typical setup of modern office lighting, by referring to the results of the survey of office lighting. Individual lighting controls for both general and task lighting were provided.

For general lighting, ceiling recessed 2 x 2 fixtures were selected as they were the most commonly used in the survey. Prismatic lenses were used in the survey to uniformly distribute the light and reduce glare. However, this type of luminaire provides only direct lighting, so its capability of reducing direct glare is limited. To reduce the glare from the fixture to the minimum, direct/indirect fixtures were also used in the survey which was thus adopted in this comparative study, as shown in Figure 3.6 (a) (b).



Figure 3.6 Lighting fixtures, light sources and lighting control devices. (a) Cree CR22 LED luminaire, (b) Philips Perform fluorescent luminaire, (c) Lite Source floor-standing task light, (d) Philips LED lamp, (e) Bulbrite T3 CFL, (f) Lutron DIVA wall dimmer, (g) Lutron Credenza CFL/LED dimmer. (Not to scale)

To approximate the linear fluorescent T8 lamps used in the ceiling recessed luminaire for general lighting, LEDs were linearly imbedded on the heat sink in the ceiling recessed LED fixture, as shown in Figure 3.7. The LED and fluorescent luminaires have almost identical light distribution. Figure 3.8 shows the luminous intensity of LED and fluorescent luminaires. Luminous intensity is defined as the amount of light emitted from a light source in a particular direction per unit solid angle. Although the initial light output of the two luminaires is different (2000 lm for LED luminaire, 2453 lm for each fluorescent luminaire), their adjusted light output could be equivalent via continuous dimming. Therefore, their luminous intensities could be assumed unified at 0 degree vertical in Figure 3.8, in order to compare the difference. From Figure 3.8, it can be seen that the luminous intensities of the two luminaires are corresponding well.

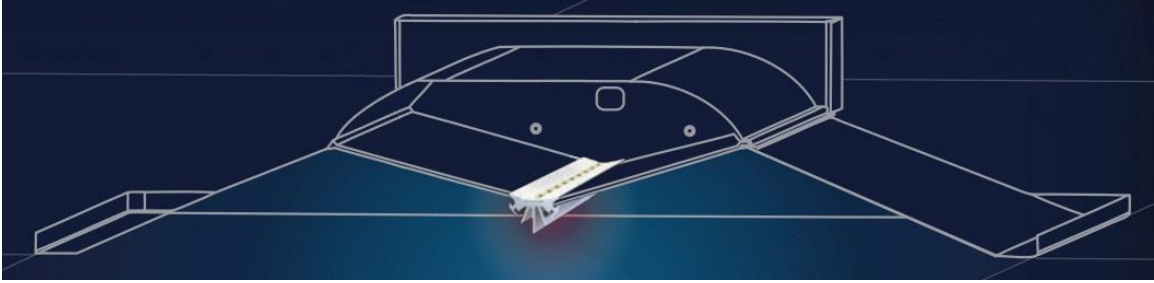
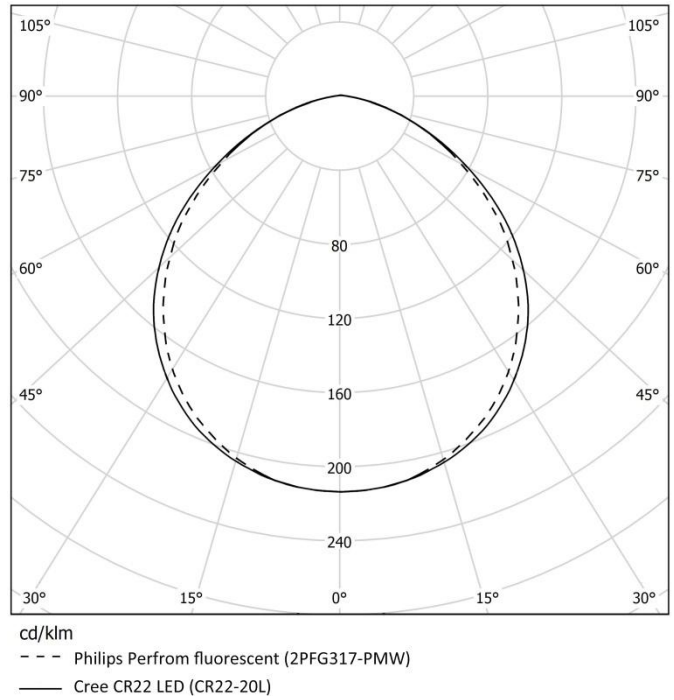
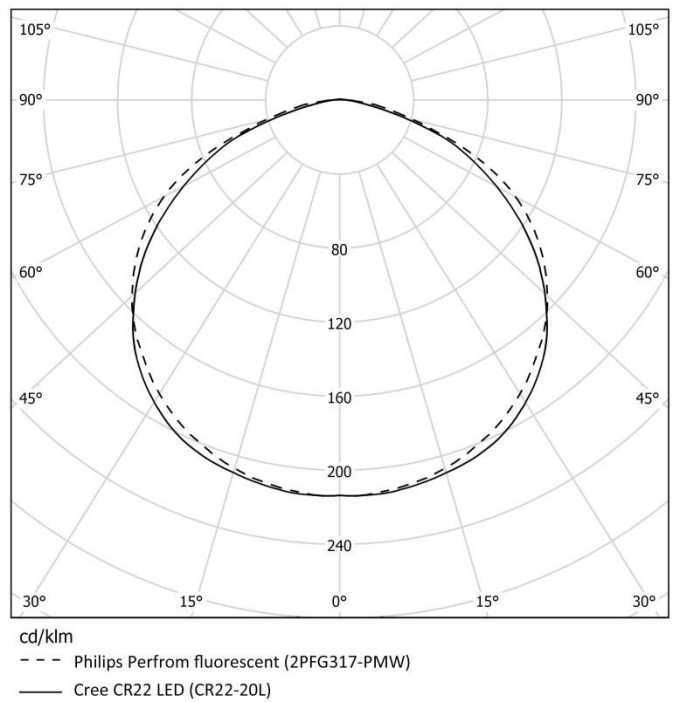


Figure 3.7 The location of embedded LEDs in ceiling recessed LED fixtures



(a)



(b)

Figure 3.8 Light distributions of Philips Perfrom fluorescent luminaire and Cree CR22 LED luminaire. Luminous intensity is normalized at 0° vertical. (a) 0° - 180° horizontal, (b) 90° - 270° horizontal.

Under both general lighting systems, the average horizontal illuminance at desk surface reached 500 lx. A dimmer was connected to the general lighting fixtures to provide individual control (Figure 3.6(f)). The dimmer was mounted on the wall next to the desk, where subjects had easy access to it.

As found in the office lighting survey, the general lighting solely in most offices could provide sufficient average horizontal illuminance of 500 lx. Task lighting was not used in most of those offices. Only four offices in the survey were equipped with task lighting. Among them, three were under-shelf linear fluorescent lamps. They were installed below the eye level of office occupants, thus preventing any direct glare from the light source.

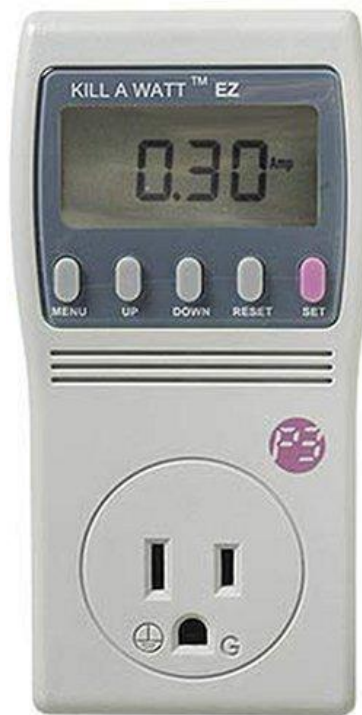
However, portable task lighting with individual control is necessary to achieve desired luminance contrasts and fit various needs of the tasks and occupants. Therefore, in this study, a portable floor-standing task lighting luminaire with adjustable arm and shade were selected for task lighting, as shown in Figure 3.6(c). The shade blocks direct lights from entering the occupant's eye to prevent direct glare. The task lighting luminaire was put on the left side of the desk to eliminate veiling reflections (IESNA 2004). A second dimmer was connected to task lighting to provide individual lighting control, as shown in Figure 3.6 (g). This dimmer was put on the desk next to the mouse, where subjects had easy access to it. A CFL (compact fluorescent lamp) was used for fluorescent lighting (Figure 3.6(e)), while an A-19 shaped LED lamp was used for LED lighting (Figure 3.6(d)). Both light sources have a CCT of 2700K and are UL certified.

An Efergy electricity monitor was used to measure the power consumption of the general lighting system (Figure 3.9(a)). A P3 International electricity usage monitor was

connected to the floor-standing task lighting luminaire to measure the power consumption of task lighting (Figure 3.9(b)). Since the power consumptions are not perfectly stable, during the experiments, power consumption measurements were conducted every 10 minutes to obtain an average value.



(a)



(b)

Figure 3.9 Energy monitors. (a) Efergy Elite Classic 3.0 Electricity Monitor, (b) P3 international P4460 Kill A Watt EZ Electricity Usage Monitor.

Detailed specifications of lighting systems are shown in Table 3.2. For both general lighting and task lighting, the mounting method, dimming control and CCT are identical under either fluorescent or LED lighting. CRI and light output were also very close. The only significant difference between the two lighting systems is the type of light sources.

Table 3.2 Specifications of lighting systems

	LED	Fluorescent
General lighting		
luminaire	4 × Cree CR22 LED direct/indirect ceiling recessed luminaire	4 × Philips Perform fluorescent direct/indirect ceiling recessed luminaire
light source	embedded LEDs	Philips 17W T8 linear fluorescent lamp
CCT	3500K	3500K
CRI	90	85
total light output	8000 lm	9812 lm
total input power	88 W	204 W
dimming	Lutron DIVA wall dimmer, continuous dimming, to 5%	
Energy monitor	Efergy Elite Classic 3.0 Electricity Monitor	
Task lighting		
luminaire	Light Source adjustable floor lamp	
light source	Philips Award Winning LED	Bulbrite T3 CFL
CCT	2700K	2700K
CRI	90	82
lumen output	940 lm	900 lm
input power	10 W	15 W
dimming	Lutron Credenza CFL/LED dimmer, continuous dimming	
Energy monitor	P3 international P4460 Kill A Watt EZ Electricity Usage Monitor	

The illuminance on task surface was contributed by both general lighting and task lighting. Therefore, to accommodate the task lighting, the general lighting was dimmed to an average horizontal illuminance of 400 lx at desk surface. This illuminance value is within the recommended values listed in Table 1.1, above. During the experiment, the general lighting was kept on 400 lx till subjects were given access to the task lighting with individual control. The subjects had choices of increasing or dimming the general lighting. Note that if subjects were only allowed to dim the light, they might have a misconception that the light level was too bright and it was proper to dim it even unnecessarily.

3.4.1.3 Office Tasks

3.4.1.3.1 Typing task

Reading and typing are common office tasks. In modern offices, workers need to view multiple displays such as paper and computer screens, and the sightline of their eyes need to scan frequently from one display to the other. Therefore, in this study, a typing task was developed, covering reading and typing performance on both paper and computer screens. In each typing task, subjects were required to type with no time limit.

The contents of the typing materials were excerpted daily from on-campus news from the official KU website and the website of “The University Daily Kansan”, the student newspaper of the University of Kansas. The selected text was easy to read and understand, and was modified to unify the length to approximately 1200 characters (including symbols and spaces). For typing practice, extra typing materials were prepared, which were instructions for the experiment. Typing materials were mounted on the

document holder, presented in high contrast, with 12 point, Calibri font, single spaced black characters printed on white letter-sized sheets, as shown in Figure 3.10. In each typing task, the typing material was unique.

The NRC Typing Task software, a freely distributed computer program developed by the National Research Council Canada (NRC n.d.), was used for evaluation of the typing task. The interface of this software has two windows. Typing materials are presented in one window while subjects type the materials in the other window. The interface of the NRC Typing Task software is shown in Figure 3.11. The color checker and gray checker below the display were used for HDR color and photometric calibrations. They were removed when subjects were in the test room. Nonetheless, in this study, the window used for presenting the typing materials was disabled. Instead, hardcopies were used, which were mounted on the document holder put close to the computer screen. Subjects were asked to type the text printed on hardcopies. The software checked the spelling word by word. When there was a spelling error, the software gave a sound alert to the subject and presented a strikethrough on the typo to show the location. Subjects could not continue till they corrected the error. As a result, once completed, the accuracy of the typing task was 100%.

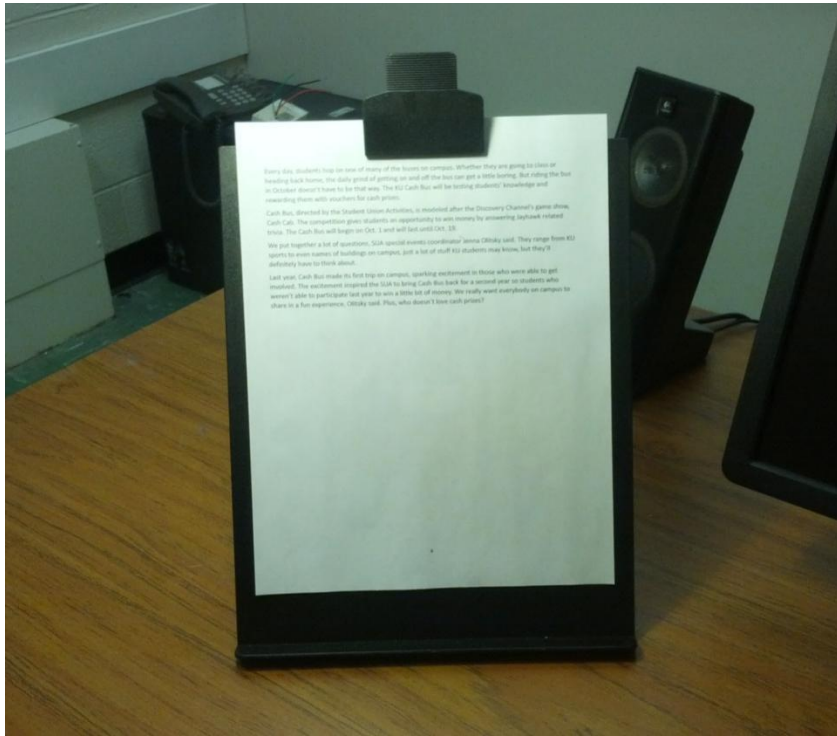


Figure 3.10 Typing materials on the document holder

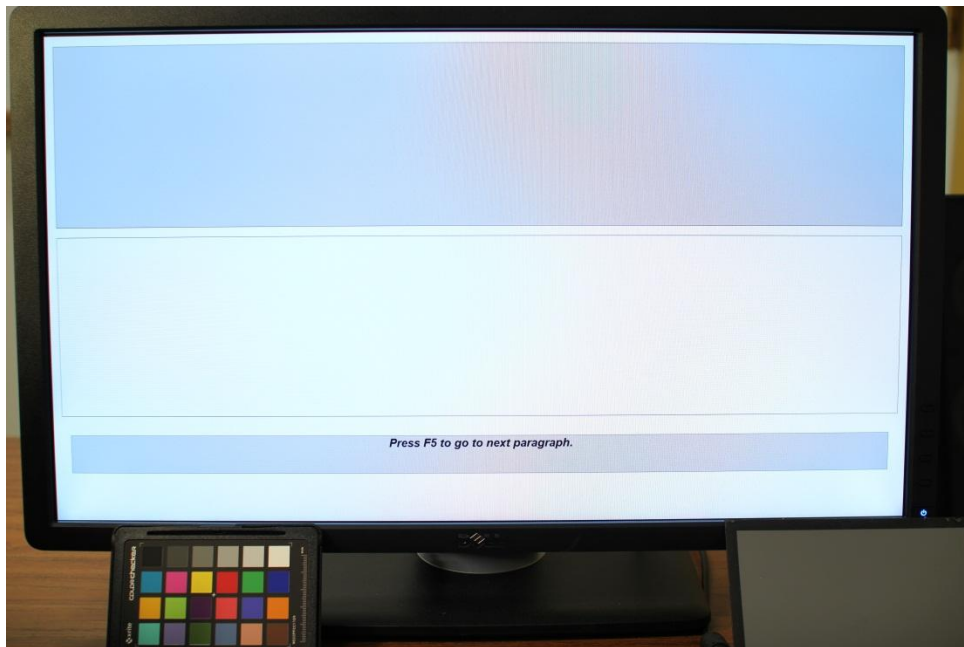


Figure 3.11 The interface of the NRC Typing Task software

The NRC Typing Task software recorded the key stroke and time. The task performance was evaluated by the typing speed. The software calculated the scores using Equation (3.1) and (3.2) (NRC n.d.). The typing task score represents the number of net characters typed per second.

$$Netchr = TOTAL - (CurKey + 2 \times BSKey) \quad (3.1)$$

$$Typing\ task\ score = \frac{NetChr}{Time} \quad (3.2)$$

Where:

CurKey = the number of cursor keys pressed;

BSKey = the number of backspace keys pressed;

TOTAL = the total number of all keys pressed including cursor and backspace keys;

NetChr = the net number of characters typed;

Time = the time spent in seconds.

3.4.1.3.2 Color Matching Task

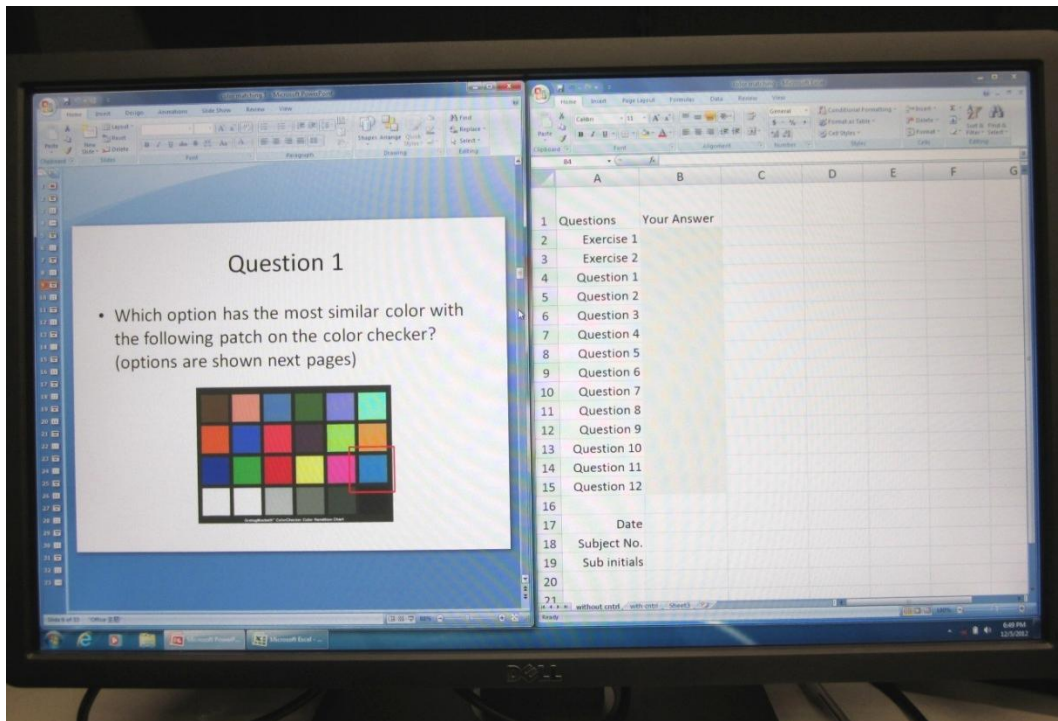
Color discrimination is also common in modern offices. Color matching task was used to evaluate the color rendering performance of the lighting. An X-rite classic color checker was mounted on the document holder (Figure 3.12). There were 18 color patches on the color checker. The six colors in the top line were defined as dark skin, light skin, blue sky, foliage, blue flower, and bluish green. The colors in the second line were defined as orange, purplish blue, moderate red, purple, yellow green, orange, and yellow. The colors in the third line were defined as blue, green, red, yellow, magenta, and cyan. During the test, dark skin was used as an example, light skin and blue sky were used in

practice, and the twelve colors in the second and third lines were used in the formal color matching task.

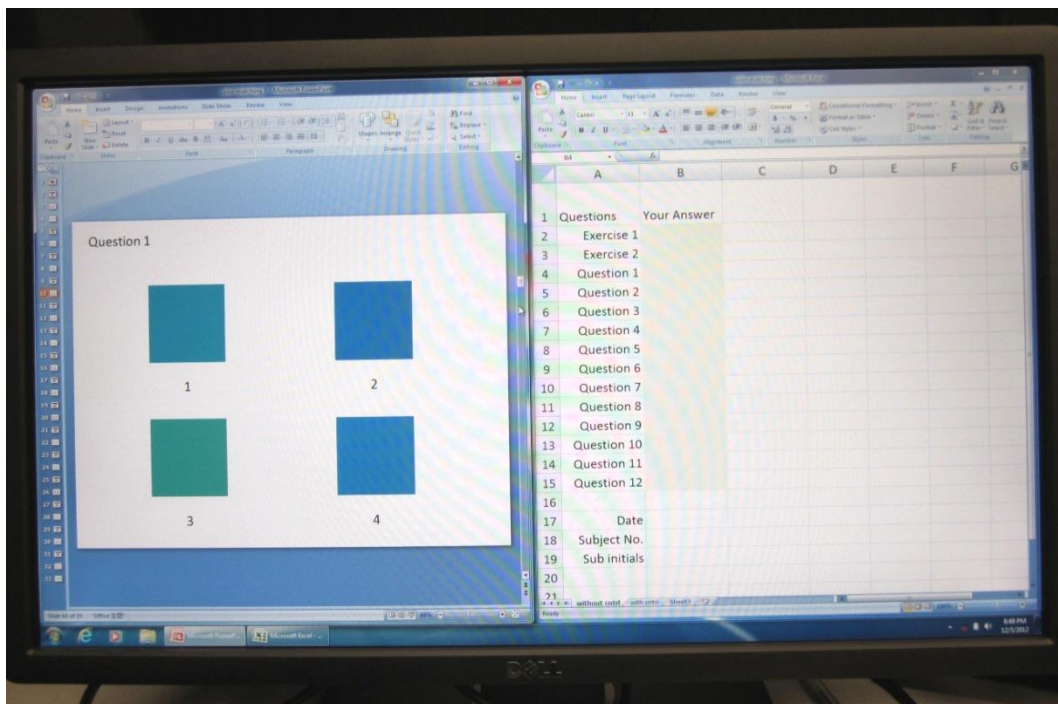


Figure 3.12 X-rite Classic Color Checker

Subjects needed to identify the bench color patch from four color options when conducting the color matching task. Figure 3.13 shows the interface of the color matching task. A Microsoft PowerPoint window was shown on the left side of the screen, while a Microsoft Excel window was shown on the right side serving as an answer sheet. Subjects were asked to find only one color patch presented on the computer screen, which was identical with the target color patch on the X-rite classic color checker. Here is the procedure: First, a slide describing the question (task) showed the subject which bench color patch on the X-rite classic color checker they should refer to (Figure 3.13(a)). Second, on the next slide, four options were shown (Figure 3.13(b)). The subject compared the four color patches shown on the screen to a corresponding bench color shown on the X-rite color checker mounted on the document holder. Third, the subject found the color patch on the screen that matched the bench color on the color checker, and typed the option number in the Excel window. In case subjects could not identify a match, they were asked to choose the closest one.



(a)



(b)

Figure 3.13 The interface of color matching task. (a) question slide, (b) options slide.

The color options shown on the computer screen were generated using adjusted RGB values in light of the bench color patch chosen from the X-rite color checker. RGB color space was chosen as it was commonly used for presenting colors in electronic systems other than CIELUV or CIELAB color spaces. Each of Red, Green and Blue values has 256 levels, ranging from 0 - 255. To generate the RGB values of each color option, an algorithm was developed from Color Blender (Color Blender), a web-based tuning tool for web design. When the RGB values of a bench color were input, six new colors that were slightly different from the bench color were generated. Among them three colors were randomly selected, together with the bench color, to form a four-choice color-matching question. The algorithm is shown in Table 3.3. A pilot study showed that by using this algorithm, the accuracy of the color-matching task ranges from 83.3% to 8.3%.

Table 3.3 The algorithm of generating candidate colors*

Colors	RGB values
Original color	R, G, B
Candidate 1: more green	R-10, G+20, B-10
Candidate 2: more yellow	R+10, G+10, B-20
Candidate 3: more red	R+20, G-10, B-10
Candidate 4: more purple	R+10, G-20, B+10
Candidate 5: more blue	R-10, G-10, B+20
Candidate 6: more cyan	R-20, G+10, B+10

*If any value drops below 0 or exceeds 255, that color will be discarded.

At the beginning, the experimenter showed an example to the subjects of how to do this color matching task. Then subjects were given two practices followed by 12 formal questions, followed by the formal color-matching task.

To ensure that subjects made their choice based on careful comparison other than a random pick of any option out of the four colors, two color matching practices were assigned before the formal color matching task. To give subjects an opportunity to get familiar with this task, Practice 1 was made easier than formal questions by enlarging the color differences among options. Practice 2 was generated with the algorithm presented above and thus had the same difficulty as that of formal questions. The two practices were assigned different difficulties in order to test that if the difficulty rises, the task performance will reduce correspondingly.

The sequence of formal questions and four options were randomized. Both the accuracy of the task and speed was recorded. The score of the color-matching task was calculated using Equation 3.3, developed in this study. The score represents the number of correct answers the subjects could make per minute.

$$\text{Color matching task score} = \frac{\text{No. of correct answers}}{\text{Time}} \quad (3.3)$$

RGB color space is device-dependent, which means a color with certain RGB values may appear different when presented on various displays. Therefore, even if the RGB values are identical, the candidate color on the computer screen may look slightly different from that on the X-rite color checker. This is actually the purpose of the test, to see the discrepancy between the paper-based and computer-screen-based color reading

commonly occurs in modern offices. Fortunately, this study used only a single computer screen and the color options shown on the screen were compared to the bench color on the X-rite color checker. The internal settings of the LCD display also remained the default factory settings without change throughout all lighting conditions. In addition, in this study task performances were compared within subjects other than between subjects. Therefore, color shifts introduced by devices were consistent for all experiments and thus were counteracted in the within-subjects comparison.

3.4.1.4 HDR photography

High Dynamic Range (HDR) photography was introduced to measure the luminance of the test room. A Canon T2i digital camera fitted with a Sigma standard lens and circular fisheye lens was used for HDR photography. The Sigma standard lens has the best correction for magnification and chromatic aberration and is capable of taking sharp images with high contrast (Sigma n.d.a). It was used to measure the immediate task surfaces, which were the VDT screen and the document holder. The Sigma circular fisheye lens has a view angle of 180 degree in all directions (Sigma n.d.b). It was used to measure the entire view of the working environment in front of the subjects.

The camera was mounted at the location of the subject's eyes to simulate the view of the subject. First, the camera was aimed at the screen. Eighteen low dynamic range (LDR) images were taken with the Sigma standard lens. Second, the camera was re-aimed at the document holder and another 18 LDR images were taken. Finally, the camera was re-aimed at the center of the screen. The standard lens was replaced with the fisheye lens and the third group of 18 LDR images was taken. An X-rite gray checker and

an X-rite color checker passport were mounted in the sight of the camera for photometric and chromatic calibration.

Each group of LDR images were then fused into one HDR images. Luminance values of every pixel were derived from the HDR images and were shown in a more illustrative way as false color images. Figure 3.14 shows sample HDR images of a certain subject under four test conditions. The HDR images were used to analyze luminance related lighting factors, such as luminance contrast, uniformity, direct/indirect glare, etc. An example of analyzing HDR images is shown below.

Luminance maps were drawn based on the luminance value of every pixel level, as shown in Figure 3.15. Warmer color represents higher luminance value. It can be seen that when given lighting control, this subject made the luminance ratio between the tasks and adjacent surfaces larger.



(a)



(b)

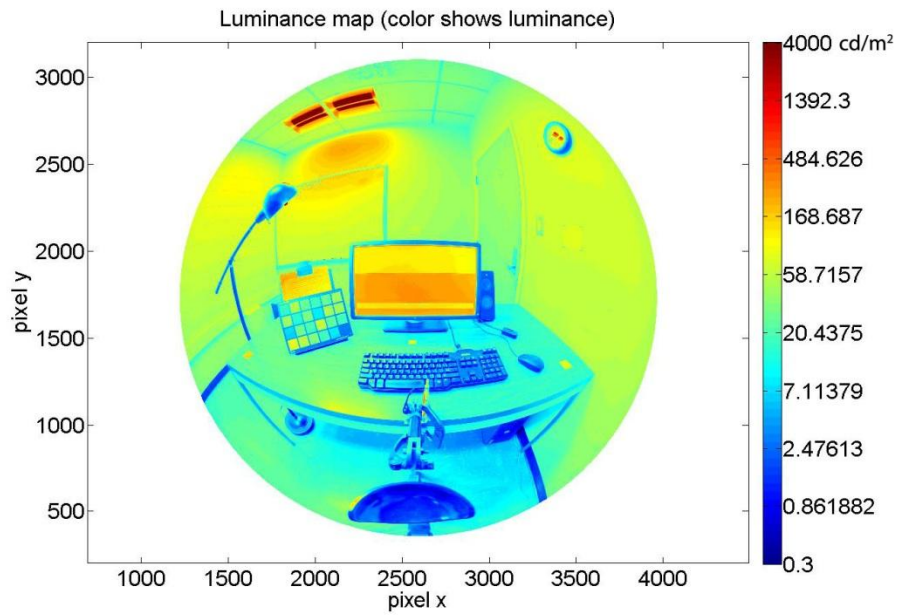


(c)

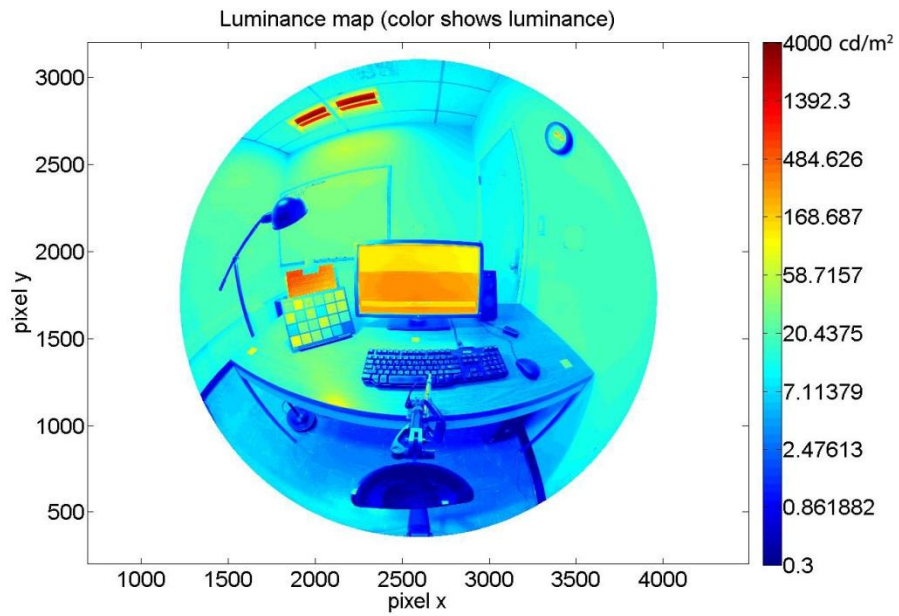


(d)

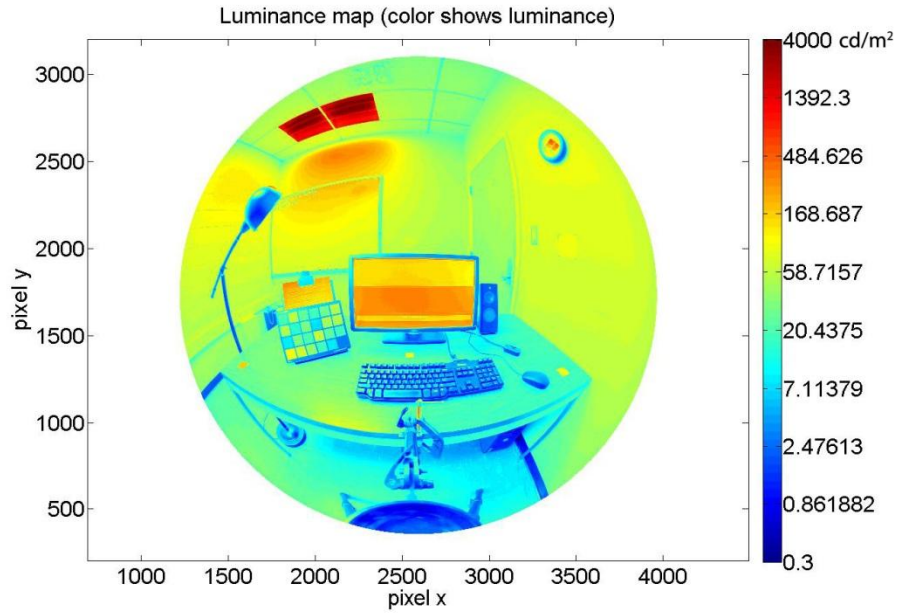
Figure 3.14 HDR images a subject under (a) LED without lighting control, (b) LED with lighting control, (c) fluorescent without lighting control, (d) fluorescent with lighting control.



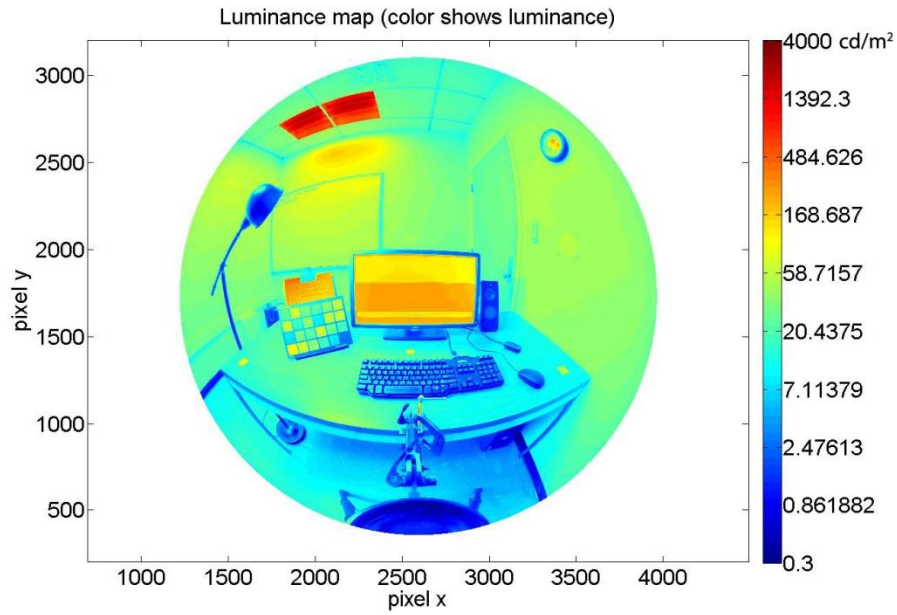
(a)



(b)



(c)



(d)

Figure 3.15 Luminance maps of a subject under (a) LED without lighting control, (b) LED with lighting control, (c) fluorescent without lighting control, (d) fluorescent with lighting control.

Luminance values of task and surrounding surfaces were derived from the HDR images. These values are shown in Table 3.4. It also reveals that when lighting control was provided, the luminance ratios between tasks and surrounding surfaces were larger. When lighting control was not available, though the general light level of LED and fluorescent lighting were both 400 lx, the luminance of LED luminaires (3810 cd/m^2) was much higher than that of fluorescent luminaires (2520 cd/m^2). This indicates that the high surface luminance of LED light sources did make the glare problem worse.

Without lighting control, the luminance ratios between document holder and VDT screen exceeded the range of 1:3 – 3:1 recommended by IES (IES 2004, 2011). However, when lighting control was available, these ratios were brought back into the recommended range. Whether with or without control, most of the luminance ratios between task and remote surfaces, which were walls in this case, fell in the range of 1:10 – 10:1 (IES 2004, 2011).

Table 3.4 Luminance values and luminance ratios in the sample HDR images

	LED without lighting control	LED with lighting control	Fluorescent without lighting control	Fluorescent with lighting control
Luminance				
(cd/m²):				
Document holder	54.9	105	60.2	71.2
VDT screen	194	207	227	192
Wall in the front	78.1	22.7	91.5	51.4
Wall on the left	56.8	18.0	63.0	31.9
Wall on the right	64.2	18.2	72.4	42.1
Luminaire	3810	977	2520	1320
Luminance ratio:				
Document holder / VDT screen	0.283	0.507	0.265	0.371
Document holder / wall in the front	0.703	4.626	0.658	1.385
Document holder / wall on the left	0.967	5.833	0.956	2.232
VDT screen / wall in the front	2.484	9.119	2.481	3.735
VDT screen / wall on the right	3.022	11.374	3.135	4.561

3.4.2 Experiment design

As typical office lighting conditions are within the range of photopic level (≥ 3 cd/m²). The adaptation of an observer's eyes to the environment should be fast given the small fluctuation of light levels throughout the whole experiment. As a result, during the experiment, subjects were given adequate time (> 2 minutes) for full adaptation whenever exposed to a new light level.

To test the impact of LED lighting technologies on office ergonomics, the experiments has a 2×2 within-subjects design. In this design, a total of four conditions were tested for two independent variables (IV). One independent variable is the type of light source (either LED or fluorescent lamps). The other independent variable is the access to individual lighting control (with or without access). The dependent variables (DV) are the typing task and color matching task scores, ratings of the lighting quality and task satisfactions.

As mentioned above, there were four test conditions: LED lighting without lighting control, LED lighting with lighting control, fluorescent lighting without lighting control, and fluorescent lighting with lighting control. Within-subjects design could reduce the effect of individual differences to the minimum because the same group of subjects went through all tests (Psychology World n.d.).

By conducting the same tasks repeatedly, subjects may get practice and performed better at the end (Psychology World n.d.). On the other hand, he/she may also gain fatigue and perform worse in the end (Psychology World n.d.). To avoid these two consequences which might put the research in harm's way, the typing material in tests under each of four lighting conditions has different contents but similar length and

difficulty. The sequence of color matching questions and options were randomized for the same reason. Additionally, before each office task, subjects were given detailed instructions on how to do the tasks and were given opportunities to practice. To relieve fatigue, subjects were given short breaks between tasks, and a 20-minute break between different test lighting conditions. During the long break, subjects were asked to leave the test room to stretch and rest.

3.4.3 Experiment Procedure

A total of 30 subjects participated in 120 tests under all four conditions.

First, the LED lighting system was installed in the test room (2135 A, Learned Hall). Subjects did office tasks under two conditions: LED lighting without lighting control and with lighting control.

After all subjects finished the experiments, the LED lighting system was replaced with a fluorescent lighting system. However, subjects were not informed of any changes in the test room. Then all subjects conducted office tasks under the other two conditions: fluorescent lighting without lighting control and with lighting control. The sequence of the experiment was randomized for different subjects. A total of 15 subjects worked without lighting control first, and then with lighting control. The other 15 subjects worked with lighting control first, and then without lighting control. For each subject, the experiment sequence under LED lighting and fluorescent lighting were the same.

To achieve the best physical comfort, before conducting the office tasks, subjects were allowed to adjust the height, arm rest, back and tilt angle of the chair as they preferred. They were also asked to feel free to adjust the position and tilt angle of the

document holder, display and keyboard, as long as the document holder was placed on the left side of the display and did not block the view of the screen. As both dimmers were placed on the right side of the desk, moving the document holder there would limit the subjects' access to the dimmers. Once the subjects finished the adjustment, they were asked to sit at a normal posture for typing. Then the experimenter helped the subject adjust the chin rest to fit the position of the subjects' heads. The subject could adjust the position and height of the chin rest till he/she felt completely comfortable. Subjects were required to remain with their chins on the chin rest throughout the process when they were conducting the office tasks. During the experiment, once adjusted initially, the chin rest, chair, display, document holder and keyboard were fixed and could not be moved any more. Of course, when the subject took the long break out of the test room, he/she was allowed to move the chair backward and forward in order to step out and then sit back down. This did not affect the resumption of the previous posture of the subject during the second stage of the experiment, as his/her chin was put on the fixed chin rest. The positions of these items were recorded for reconstruction except for the chair.

For experiments with individual controls available, subjects were asked to adjust both general lighting and task lighting to levels as they preferred. They were also asked to adjust the brightness of the screen to achieve a proper luminance contrast. Subjects were given detailed instructions on how to adjust the lighting condition but no hints as to which light level to use. It was found in previous studies that having experience with the working environment could lead to a better ability to achieve a comfortable lighting condition when lighting control was available (Veitch & Newsham 2000a, Veitch and Gifford 1996). Therefore, subjects were given unlimited time to adjust the lighting.

In addition, when subjects finished the initial adjustment of the lighting, they were given a short typing exercise in order to evaluate if the lighting condition really fit their needs during the tasks. If not, further adjustments were needed and granted. Once the adjustment was finalized, the lighting condition was fixed throughout the rest of the experiment.

Detailed experiment procedures under each lighting condition are shown in Table 3.4.

Table 3.5 Experiment procedures, first without lighting control, and then with lighting control*

Steps	Procedures	Activity
1	Pre-experiment preparation	Dim general lighting to average horizontal illuminance of 400 lx.
2	Subject arrival	Subject arrives. Give the subject eyesight test. Ask if the subject has normal color vision. Give brief instructions, subject reads and signs the consent form.
3	Physical adjustments	Subject adjusts the chair, display, document holder and keyboard. Adjusts the chin rest.
4	Lighting condition reset	Ask the subject to step out of the test room, dim the task lighting until the illuminance values on the surface of the color checker and the screen were the same, about 350 lx. Ask the subject to come back in and sit down. Give at least 2 minutes for adaptation.
5	Typing tasks without lighting control	Give instructions. Subject practices. Subject does the formal typing task Give subject a short break.
6	Color matching tasks without lighting control	Give instructions. Subject practices. Subject does the formal color matching task.
7	Questionnaire	Subject does the questionnaire.
8	Break & Photometric measurements	Subject steps out of the test room and has a 20-minute break. HDR photography. Measure the illuminance and CCT of the test room

		at sample points.
		Subject comes back.
9	Individual lighting control	Instructions. Subject adjusts the lighting condition. Give at least 2 minutes for adaptation.
10	Typing tasks with lighting control	Give instructions. Subject practices. Subject does the formal typing task Give subject a short break.
11	Color matching tasks with lighting control	Give instructions. Subject practices. Subject does the formal color matching task.
12	Questionnaire	Subject does the questionnaire.
13	Finishing	Payment. Subject leaves.
14	Photometric measurements	HDR photography. Measure the illuminance and CCT of the test room at sample points.

*For reversed experiment sequence (first with lighting control, and then without lighting control), step 4, 5, 6 were switched with step 9, 10, 11.

CHAPTER 4 DATA ANALYSES AND RESULTS

4.1 Introduction

The data collected in the experiment were then analyzed to look into the effects of LED lighting technologies on office ergonomics. Evaluations of five different metrics were conducted as follows: First, the performance of the typing task was evaluated using the net characters typed per second. Second, the performance of the color matching task was evaluated by the number of correct responses per minute. Third, the lighting quality of the test office was evaluated using frequency and percentage of positive responses obtained from the subjects. Fourth, the lighting power consumption was evaluated using the average watt of both general and task lighting, and the percentage of power savings achieved by replacing fluorescent light sources with LEDs. These evaluations are explained below.

The mean values of each metric under four test conditions were compared to see if there were statistical differences among them. Analysis of variance (ANOVA) is the typical method to compare means. As discussed in Chapter 3.4.2, 2×2 within-subjects design was used in this study. The individual differences (ages, visual acuities, light level preferences, etc.) among all 120 experiments were not independent because a group of 30 subjects went through all four test conditions. This violated the assumption of standard ANOVA that all factors among random trials shall be independent (IDRE n.d.). Therefore, standard ANOVA cannot be used in this study. If the samples in the experiment are correlated, repeated measures ANOVA should be used (IDRE n.d.).

Repeated measures ANOVA is designed to test the equality of means when a sample is exposed to different conditions in turn, in this case, a group of subjects was

exposed to four lighting conditions in turn. However, repeated measures ANOVA can only test if there is any significant difference among the means of test conditions. It cannot distinguish between which two means the difference occurs and the polarity of the difference. Thus, post-hoc tests were also conducted to compare means in pairs. In this study, paired samples T-test was used in post-hoc tests. Like repeated measures ANOVA, paired samples T-test is capable of comparing means when the samples of the experiment are correlated.

In post-hoc tests, the mean values under four test conditions were compared in four pairs: LED with lighting control vs. LED without lighting control, fluorescent without lighting control vs. fluorescent with lighting control, LED without lighting control vs. fluorescent without lighting control, and LED with lighting control vs. fluorescent with lighting control. In each pair, only one independent variable (IV) was involved. LED without lighting control vs. fluorescent with lighting control and LED with lighting control vs. fluorescent without lighting control were not compared, because two IVs were involved.

Questionnaires used in this study consisted of 17 close-ended questions with only two options: agree or disagree, so the responses to these questions were discrete. This violated the assumption of ANOVA and T-test that the dependent variables must be continuous. Therefore, the responses of these questions could not be analyzed by ANOVA or T-test. Alternatively, Chi-square test was used, which was capable of analyzing discrete variables.

All tests were analyzed at a confidence level of 0.05 ($\alpha=0.05$) with IBM SPSS.

4.2 Performance of the Office Tasks

4.2.1 Typing task performance

The mean scores of each test condition, which are used to evaluate the typing speed of the subjects with 100% accuracy, are shown in Table 4.1 and Figure 4.1. It was found that the subjects' average speed at four different test conditions was actually very close. There are no outliers in the box plot (Figure4.1).

Table 4.1 Descriptive statistics of typing task scores.

	Mean	Std. Deviation	No. of subjects
LED without lighting control	4.17002680	1.378444532	30
LED with lighting control	4.12034423	1.397831383	30
fluorescent without lighting control	4.04504220	1.324095675	30
fluorescent with lighting control	3.99745690	1.323027108	30

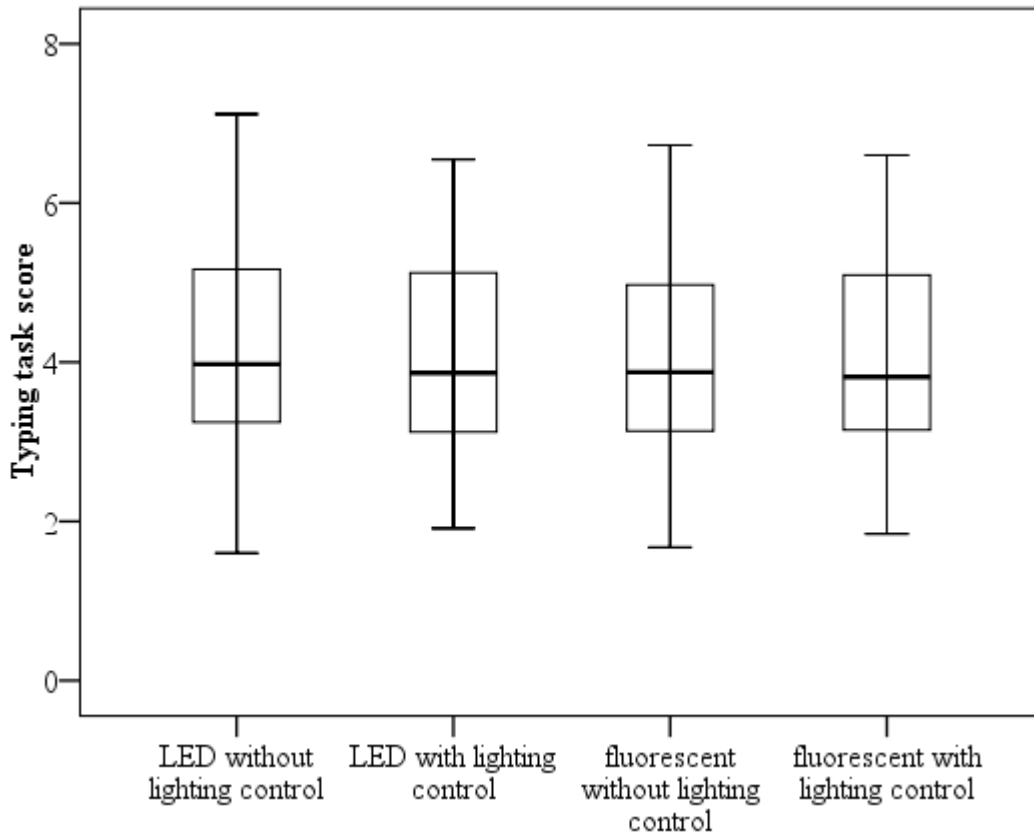


Figure 4.1 Typing task scores under four test conditions

The results of repeated measures ANOVA is shown in Table 4.2. The p value which is less than 0.05 is presented in bold. The dependent variable (DV) is the typing task score, while the independent variables (IV) include the type of light source and the lighting control. Based on the results, significant difference of the typing task performance was found under different light sources (LED vs. fluorescent) ($p=0.019$). Nonetheless, the lighting controls did not make any statistically significant difference ($p=0.527$) on the typing task performance. Likewise, no significant interaction was found between lighting source and lighting control ($p=0.981$).

Table 4.2 Tests of repeated measures ANOVA for typing task scores

Source	Type III Sum			F	Sig.
	of Squares	df	Mean Square		
light source	0.461	1	0.461	6.163	0.019
Error(light source)	2.168	29	0.075		
lighting control	0.071	1	0.071	0.410	0.527
Error(lighting control)	5.020	29	0.173		
light source * lighting control	3.299E-5	1	3.299E-5	0.001	0.981
Error(light source * lighting control)	1.582	29	0.055		

To better reveal the differences of typing speed caused by the type of light source, paired samples T-tests were conducted, see Table 4.3. Since all of resulting p values are larger than 0.05, we can claim that no statistically significant differences of typing speed were found between paired conditions.

The result shows that although the repeated measures ANVOA showed a significant impact of the type of light sources on the typing task score, the post-hoc T-tests revealed that no significant differences were found. As discussed in Chapter 4.1, the alternative hypothesis of repeated measures ANOVA is “at least two means are significantly different”. It cannot tell between which two means the difference occurs and the polarity of the difference. Therefore, the result of repeated measures ANOVA alone is insufficient. On the other hand, post-hoc T-tests compared the means in pairs. Therefore, we believe that the result of post-hoc T-tests is more reliable. Neither the type of the light sources (LED or fluorescent) nor the access to lighting control (with or without) had significant impact on typing task scores.

Table 4.3 Paired samples T-Tests for typing task scores

		Paired Differences							
		95% Confidence Interval of the					Sig. (2-tailed)		
Pair		Mean	Std. Deviation	Std. Error	Difference				
				Mean	Lower	Upper	t	df	
Pair 1	LED without lighting control – LED with lighting control	0.049682567	0.529834741	0.096734146	-0.148160977	0.247526110	0.514	29	0.611
Pair 2	fluorescent without lighting control – fluorescent with lighting control	0.047585300	0.417885606	0.076295124	-0.108455750	0.203626350	0.624	29	0.538
Pair 3	LED without lighting control – fluorescent without lighting control	0.124984600	0.346821673	0.063320685	-0.004520741	0.254489941	1.974	29	0.058
Pair 4	LED with lighting control – fluorescent with lighting control	0.122887333	0.372015491	0.067920425	-0.016025534	0.261800200	1.809	29	0.081

4.2.2 Color matching task performance

The mean scores of each test conditions are shown in Table 4.4 and Figure 4.2. It was found that the performance of color matching tasks was not as consistent as that of the typing tasks, with three outliers in Figure 4.2. A repeated measures ANOVA was conducted. The dependent variable (DV) is the color matching score, and the independent variables (IV) are the type of light source and lighting control. The result is shown in Table 4.5. It was found that different light sources did not have a significant effect on the subjects' performance of color matching tasks ($p=0.310$). However, the lighting control has a significant difference on color matching performance ($p=0.047$). There is no significant interaction between the performance under different lighting sources and using different lighting controls ($p=0.299$).

Table 4.4 Descriptive Statistics of color matching task scores

	Mean	Std. Deviation	No. of subjects
LED without lighting control	1.08314734	0.439225732	30
LED with lighting control	1.00981638	0.538673875	30
fluorescent without lighting control	1.06262891	0.644981662	30
fluorescent with lighting control	0.84464133	0.474429897	30

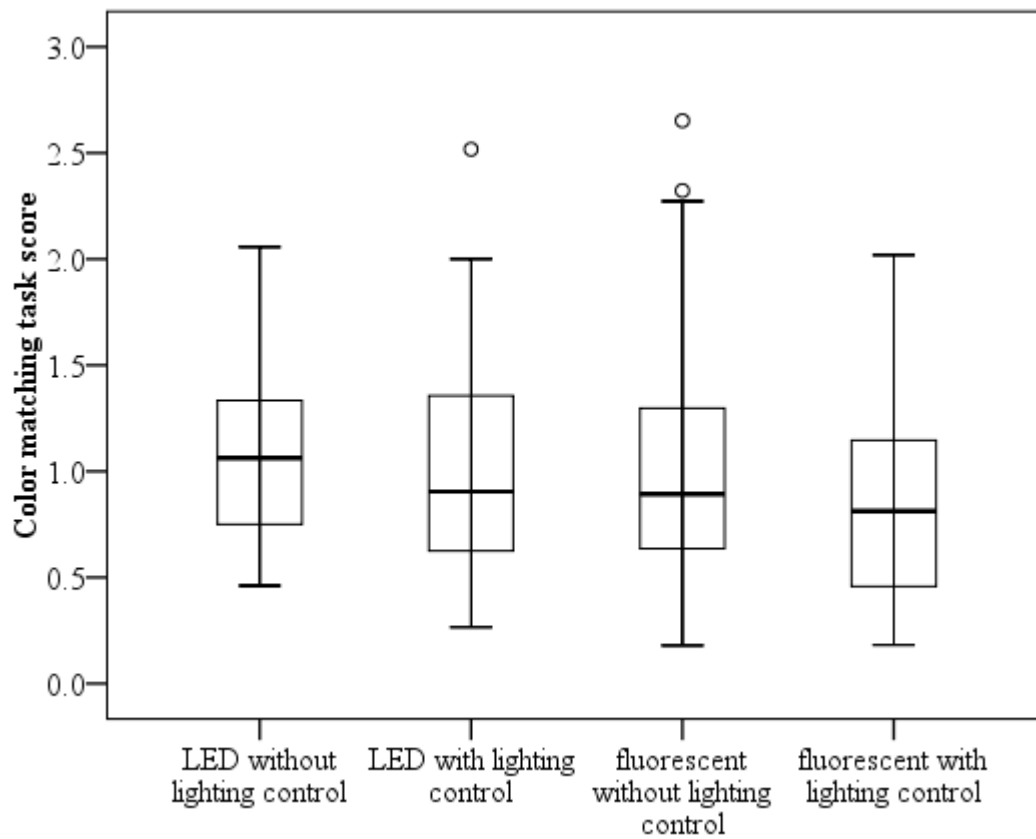


Figure 4.2 Typing task scores under four test conditions

Table 4.5 Tests of repeated measures ANOVA for color matching task scores

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Light source	0.259	1	0.259	1.066	0.310
Error(light source)	7.038	29	0.243		
Lighting control	0.636	1	0.636	4.293	0.047
Error(lighting control)	4.300	29	0.148		
Light source * lighting control	0.157	1	0.157	1.120	0.299
Error(light source * lighting control)	4.065	29	0.140		

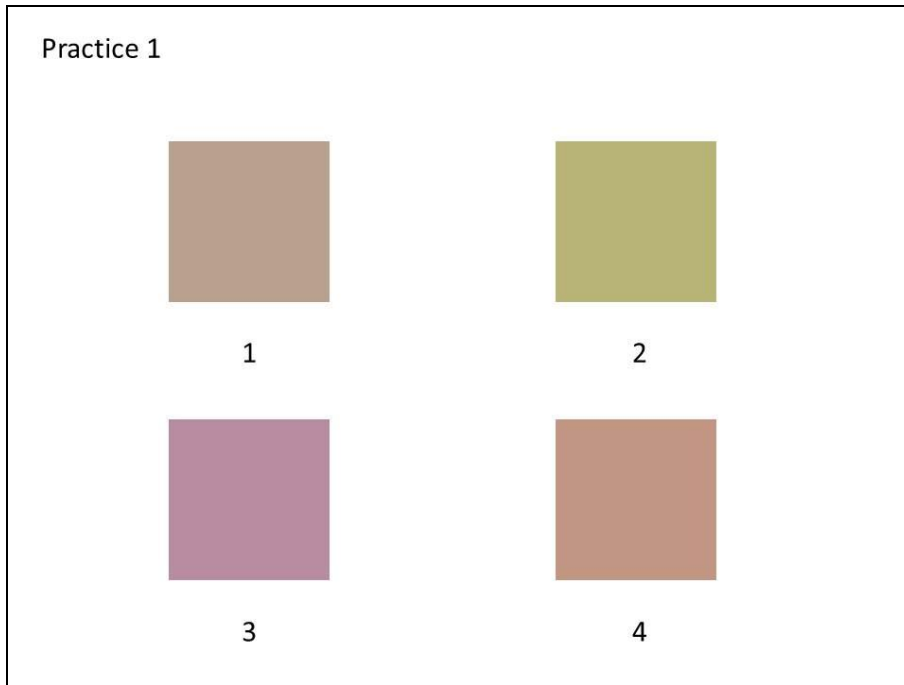
To better reveal the significant difference of color matching task scores found in ANOVA, post-hoc T-tests were then conducted in four pairs. The result is shown in Table 4.6. It is found that the mean color matching scores between two paired conditions are significantly different: fluorescent without lighting control vs. fluorescent with lighting control ($p=0.032$), LED without lighting control vs. fluorescent with lighting control ($p=0.022$). According to Table 4.4 above, under fluorescent lighting, with introduction of the individual lighting controls, the mean score of the color matching tasks decreased by 20.5% (from 1.06262891 to 0.84464133). There is no significant difference between any other paired test conditions, as the p values are larger than 0.05.

Table 4.6 Paired samples T-tests for color matching task scores

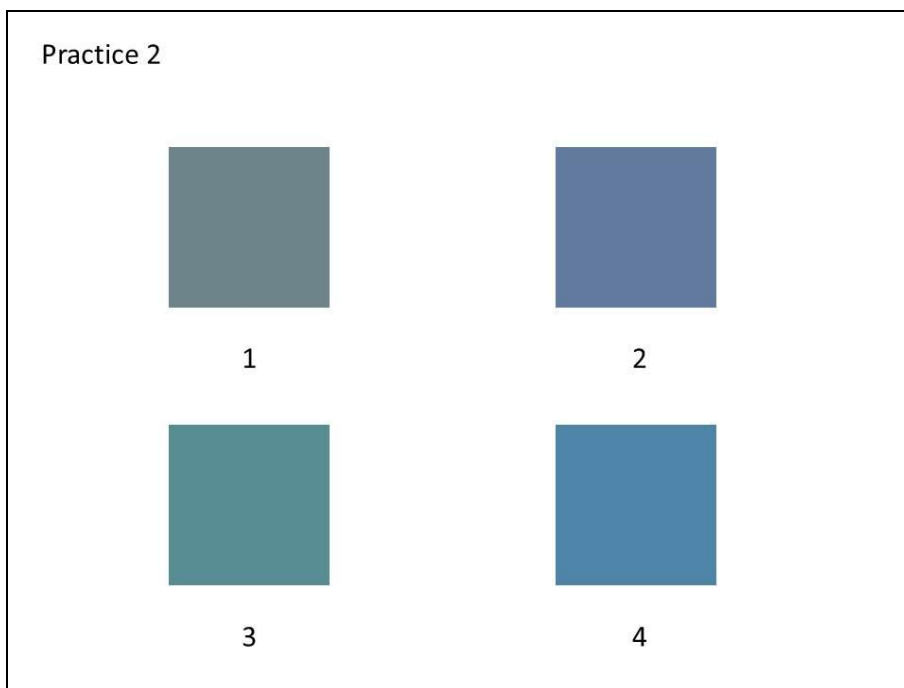
		Paired Differences							
		Mean	Std. Deviation	Std. Error	95% Confidence Interval of the Difference		t	df	Sig. (2-tailed)
				Mean	Lower	Upper			
Pair 1	LED without lighting control – LED with lighting control	0.073330965	0.542907665	0.099120925	-0.129394089	0.276056019	0.740	29	0.465
Pair 2	fluorescent without lighting control – fluorescent with lighting control	0.217987579	0.531181215	0.096979978	0.019641253	0.416333904	2.248	29	0.032
Pair 3	LED without lighting control – fluorescent without lighting control	0.020518434	0.671819036	0.122656814	-0.230342917	0.271379785	0.167	29	0.868
Pair 4	LED with control – fluorescent with lighting control	0.165175048	0.560702530	0.102369808	-0.044194718	0.374544813	1.614	29	0.117

To help subjects become familiar with the color matching task, two practices were given before they conducted the formal color matching tasks. Practice 1 was intentionally made easier than Practice 2. In practice 1, the accuracy of color matching was 95.0%, with a standard deviation of 0.22%. In practice 2, the accuracy of color matching was 43.3%, with a standard deviation of 0.50%. The accuracy of color matching decreased and the standard deviation increased as the difficulty of the practice increased. The options of color matching practices are shown in Figure 4.3. In Practice 1, the RGB values of Option 1 – 4 are: (184, 160, 140), (184, 180, 120), (184, 140, 160), (194, 150, 130). Option 4 is the correct answer. The corresponding color patch on the color checker is the second patch in the first line, see Figure 3.11. In Practice 2, the RGB values of Option 1 – 4 are: (108, 132, 137), (98, 122, 157), (88, 142, 147), (78, 132, 167). Option 2 is the correct answer. The corresponding color patch on the color checker is the third patch in the first line, see Figure 3.11. The components of the subjects' responses on different options are shown in Figure 4.4. It can be seen that the percentages of options were significantly unbalanced. Subjects' responses to Practice 1 mainly focused on Option 4, while that of Practice 2 focused on Options 1 and 2. This indicates that subjects seriously completed their color matching task rather than guessing randomly, since otherwise the percentage of each option should be 25%, statistically.

The results reveal that using different types of light sources (LED or fluorescent) alone did not have significant impact on the subjects' performance of color matching tasks. In addition, introduction of individual lighting control did not have significant effect on the performance of color matching tasks conducted under the LED lighting, but significantly lowered the color matching task scores under fluorescent lighting.

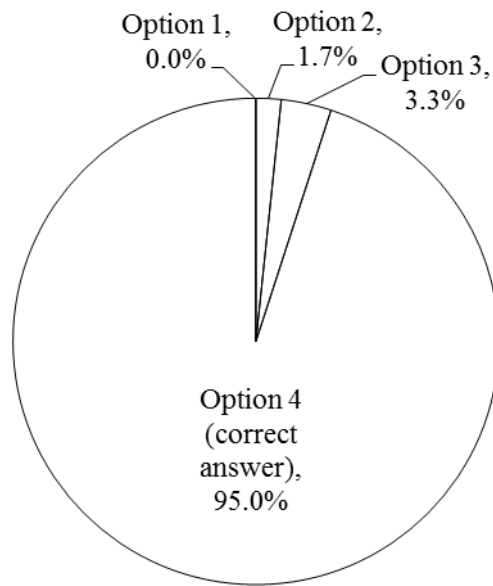


(a)

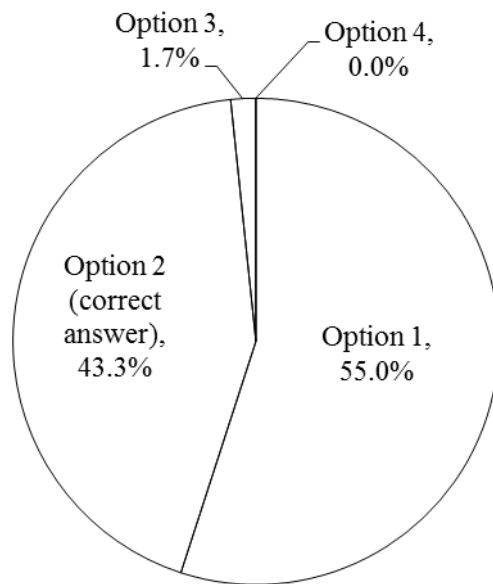


(b)

Figure 4.3 Options of color matching practices, (a) Practice 1, (2) Practice 2.



(a)



(b)

Figure 4.4 Components of responses in color matching practices, (a) Practice 1, (b) Practice 2.

4.3 Questionnaire Results

4.3.1 Lighting Quality Survey

The first part of the questionnaire is a survey on lighting quality, which consists of 17 close-ended questions with only two options: agree or disagree. Chi-square tests were conducted to analyze these questions. The dependent variable (DV) is the frequency of the positive responses, and the independent variables (IV) are the type of the lighting sources (LED vs. fluorescent) and the access to the lighting control (with or without).

Among those questions on lighting quality, some are asked in a positive tone, like “Overall, the lighting is comfortable”. While the others are asked in a negative tone such as “The lighting is uncomfortably bright for the tasks that I perform”. For questions asked in a positive tone, a response of “agree” means subjective feeling of good lighting quality. For questions asked in a negative tone, a response of “agree” indicates subjective feeling of bad lighting quality. Therefore, to clear the confusion and combine the data, we used the responses to the positive and negative lighting quality for further data analyses, which is independent of how those questions were asked and was used to unify the answers of those questions. The descriptive statistics of answers to the 17 questions on lighting quality and results of the Chi-square tests are shown in Table 4.7.

Table 4.7 Descriptive statistics and Chi-square test results for lighting quality survey

Question no.	Frequency and percentage of positive responses								Chi-square test p value
	LED w/o lighting control		LED with lighting control		fluorescent w/o lighting control		fluorescent with lighting control		
1	26	(86.7%)	28	(93.3%)	23	(76.7%)	28	(93.3%)	0.164
2	29	(96.7%)	28	(93.3%)	30	(100.0%)	28	(93.3%)	0.513
3	24	(80.0%)	26	(86.7%)	25	(83.3%)	27	(90.0%)	0.727
4	27	(90.0%)	28	(93.3%)	27	(90.0%)	27	(90.0%)	0.960
5	28	(93.3%)	27	(90.0%)	28	(93.3%)	25	(83.3%)	0.528
6	25	(83.3%)	26	(86.7%)	28	(93.3%)	29	(96.7%)	0.295
7	26	(86.7%)	29	(96.7%)	26	(86.7%)	30	(100.0%)	0.165
8	27	(90.0%)	28	(93.3%)	29	(96.7%)	28	(93.3%)	0.784
9	29	(96.7%)	26	(86.7%)	29	(96.7%)	27	(90.0%)	0.356
10	28	(93.3%)	28	(93.3%)	21	(70.0%)	25	(83.3%)	0.035
11	28	(93.3%)	30	(100.0%)	28	(93.3%)	30	(100.0%)	0.247
12	26	(86.7%)	28	(93.3%)	20	(66.7%)	25	(83.3%)	0.046
13	29	(96.7%)	30	(100.0%)	29	(96.7%)	30	(100.0%)	0.565
14	30	(100.0%)	28	(93.3%)	30	(100.0%)	29	(96.7%)	0.288
15	26	(86.7%)	28	(93.3%)	21	(70.0%)	24	(80.0%)	0.103
16	27	(90.0%)	26	(86.7%)	22	(73.3%)	28	(93.3%)	0.128
17	24	(80.0%)	23	(76.7%)	21	(70.0%)	26	(86.7%)	0.466

It is found that only answers to questions 10 and 12 were affected by the test conditions. Question 10 is “The lighting is too warm for me or my work” ($p=0.035$) and Question 12 is “The lighting color temperature is just fine for me or my work” ($p=0.046$). So far the results cannot tell exactly which independent variables caused the differences. To solve this problem, further Chi-square tests were conducted to compare the test conditions in pairs. The dependent variable (DV) is the frequency of the positive responses, and the independent variables (IV) are the type of the lighting sources (LED vs. fluorescent) and the access to the lighting control (with or without). The result is shown in Table 4.8. It was found that for fixed lighting without lighting control, replacing fluorescent lamps with LEDs had a statistically significant impact on the responses to Question 10 ($p=0.020$). According to Table 4.7, when lighting control was not available, the percentage of positive responses to Question 10 was significantly reduced from 93.3% to 70.0%, after changing the light sources from LEDs to fluorescent.

Table 4.8 Chi-square test results for Questions 10 and 12

Paired test conditions	P value	
	Question 10	Question 12
LED with lighting control - LED without lighting control	1.000	0.389
fluorescent with lighting control - fluorescent without lighting control	0.222	0.136
LED without lighting control - fluorescent without lighting control	0.020	0.067
LED with lighting control - fluorescent with lighting control	0.228	0.228

For fixed lighting without lighting control, replacing fluorescent lamps with LEDs made subjects have better feelings about the CCT of the lighting. To better explain this phenomenon, the average CCTs of some sample points identified in the test scenario are listed in Table 4.9. The locations of the sample points were shown in Figure 3.3. Points 1 – 3 were on the desk surface. Point 4 was on the center of document holder. Point 5 was on the screen. Points 6 – 8 were on the walls, 4 ft. above the ground, which is close to the eye level of sitting office occupants. The nominated CCTs of LED and fluorescent lamps are the same (3000 K for general lighting, 2700 K for task lighting), which were obtained from the cut-sheets of the manufacturers. However, it was shown in Table 4.9 that during the experiment, the mean CCTs of fluorescent lighting were constantly about 100 Kelvin lower than those of LED lighting, regardless of the access to lighting control. The low CCT of fluorescent lighting might make the subject feel uncomfortably warm. For fixed lighting without lighting control, this difference of the subjects' discomfort is statistically significant ($p=0.020$). However, after introducing lighting control, this difference of discomfort was no longer statistically significant ($p=0.228$).

Table 4.9 Average CCT at sample points

No. of sample points	Frequency and percentage of positive attitudes			
	LED w/o lighting control	LED with lighting control	fluorescent w/o lighting control	fluorescent with lighting control
1	3235.6	3181.2	3145.5	3109.9
2	3157.2	3035.2	3080.6	2966.2
3	3180.3	3145.0	3092.3	3067.8
4	3033.1	2988.3	2836.9	2824.4
5	2976.1	2903.1	2839.0	2794.3
6	3041.8	3005.6	2964.3	2942.6
7	3213.0	3179.7	3121.6	3104.6
8	3165.1	3133.1	3037.1	3050.7
Average of all sample points	3125.3	3071.4	3014.7	2982.6

4.3.2 Task satisfaction

Similar to symptoms ratings, task satisfaction was rated on a 0 – 4 scale. 0 means the least satisfied, and 4 means the most satisfied. Also, task difficulties were rated from 0 to 4. 0 means the least difficult, 4 means the most difficult. Descriptive statistics of task satisfaction ratings are shown in Table 4.10. A repeated measures ANOVA was conducted. The dependent variable (DV) is the rating of task difficulties and task satisfactions, and the independent variables (IV) are the type of lighting source and access to individual lighting control. The result is shown in Table 4.11. Type of lighting source (LED or fluorescent) had a significant impact on the ratings of typing task difficulty ($p=0.006$). Post-hoc T-tests were conducted, as shown in Table 4.12.

The results of post-hoc T-Tests show that when lighting control was available to the subjects, using different types of light sources (LED or fluorescent) had a statistically significant impact on the subjects' ratings of the typing task difficulty ($p=0.037$). According to Table 4.10, when lighting control was available, the ratings of the typing task difficulty dropped from 1.2 to 0.8 after the fluorescent light sources were replaced with LEDs.

Table 4.10 Descriptive statistics of task satisfaction ratings

Question No.	LED w/o lighting control		LED with lighting control		fluorescent w/o lighting control		fluorescent with lighting control	
	Mean	SD*	Mean	SD	Mean	SD	Mean	SD
22	0.9	0.81	0.8	0.76	1.1	0.72	1.2	0.90
23	2.8	1.07	2.9	0.68	3.1	0.73	2.8	0.97
24	2.3	0.89	2.1	0.99	2.1	0.96	1.9	0.89
25	2.7	0.86	2.6	0.80	2.8	0.73	2.9	0.79

*SD= standard deviation

Table 4.11 Tests of 2 × 2 repeated measures ANOVA for Question 22 – 25

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Question 22: How do you rate the difficulty of the typing task you did?					
Light source	3.333	1	3.333	8.657	0.006
Error(Light source)	11.167	29	0.385		
Lighting control	0.033	1	0.033	0.102	0.752
Error(Lighting control)	9.467	29	0.326		
Light source * Lighting control	0.133	1	0.133	0.340	0.564
Error(Light source * Lighting control)	11.367	29	0.392		
Question 23: How do you rate your satisfaction with your typing task performance?					
Light source	0.133	1	0.133	0.195	0.662
Error(Light source)	19.867	29	0.685		
Lighting control	0.133	1	0.133	0.177	0.677
Error(Lighting control)	21.867	29	0.754		
Light source * Lighting control	0.833	1	0.833	2.164	0.152
Error(Light source * Lighting control)	11.167	29	0.385		
Question 24: How do you rate the difficulty of the color matching task you did?					
Light source	1.200	1	1.200	1.561	0.222
Error(Light source)	22.300	29	0.769		
Lighting control	0.533	1	0.533	1.410	0.245
Error(Lighting control)	10.967	29	0.378		
Light source * Lighting control	0.000	1	0.000	0.000	1.000
Error(Light source * Lighting control)	14.500	29	0.500		
Question 25: How do you rate your satisfaction with your color matching task performance?					
Light source	1.633	1	1.633	2.326	0.138
Error(Light source)	20.367	29	0.702		
Lighting control	0.033	1	0.033	0.097	0.758
Error(Lighting control)	9.967	29	0.344		
Light source * Lighting control	0.300	1	0.300	1.000	0.326
Error(Light source * Lighting control)	8.700	29	0.300		

Table 4.12 Paired sample T-test results for responses of Question 22: the difficulty of the typing task

		Paired Differences							
		Mean	Std. Deviation	Std. Error	95% Confidence Interval of the Difference		t	df	Sig. (2-tailed)
					Mean	Lower			
Pair 1	LED without lighting control – LED with lighting control	0.100	0.712	0.130	-0.166	0.366	0.769	29	0.448
Pair 2	fluorescent without lighting control – fluorescent with lighting control	-0.033	0.964	0.176	-0.393	0.327	-0.189	29	0.851
Pair 3	LED without lighting control – fluorescent without lighting control	-0.267	0.740	0.135	-0.543	0.010	-1.975	29	0.058
Pair 4	LED with lighting control – fluorescent with lighting control	-0.400	1.003	0.183	-0.775	-0.025	-2.183	29	0.037

4.4 Lighting Power consumption

Lighting power consumptions were measured by two energy monitors: Efergy Elite Classic 3.0 Electricity Monitor for general lighting, and P3 international P4460 Electricity Usage Monitor. The readings of monitors were recorded every ten minutes to obtain average values, as shown in Table 4.13. It was found that for fixed lighting without lighting control, lighting power consumption reduced by 60.9% after the fluorescent light sources were replaced with LEDs. For adjustable lighting with lighting control, lighting power consumption could be reduced by 65.5% after the fluorescent light sources were replaced with LEDs. The total power savings of adjustable lighting after the fluorescent light sources were replaced with LEDs is higher than that of fixed lighting. This result indicates that by introducing lighting control, higher lighting efficiency could be achieved without negative impacts on the task performances or subjective satisfactions.

Table 4.13 Lighting power consumptions

	Lighting Power consumption (W)					
	General lighting		Task lighting		Total	
	Mean	SD*	Mean	SD	Mean	SD
Without lighting control:						
Fluorescent	162.7	4.10	10.9	0.45	173.6	4.35
LED	62.9	1.06	5.0	1.16	67.9	1.70
Percentage of power saving after replacing fluorescent lamps with LEDs	61.3%		54.1%		60.9%	
With lighting control:						
Fluorescent	148.4	27.13	12.1	1.34	160.5	27.23
LED	48.1	21.24	7.3	2.61	55.4	21.76
Percentage of power saving after replacing fluorescent lamps with LEDs	67.6%		39.7%		65.5%	

*SD = standard deviation

CHAPTER 5 CONCLUSIONS AND DISCUSSION

5.1 Conclusions

The experiment results revealed that LED technologies have significant impact on several aspects of office ergonomics. They are detailed below.

1. Under LED lighting, introduction of individual lighting control did not affect color matching task performance in this study. However, under fluorescent lighting, introducing lighting control lowered the color matching task score by 20.5%. As a result, the color perception of subjects in this study under LED lighting was more consistent than that under fluorescent lighting.
2. In this study, although LED and fluorescent light sources had the same nominal CCT (3500K for general lighting, and 2700K for task lighting), which was obtained from the cut-sheets of the manufacturers, the actual CCT of fluorescent lighting was 100 Kelvin lower than that of LED lighting. As a result, subjects felt the color temperature of the light uncomfortably warm under fluorescent lighting. This uncomfortable feeling could be eliminated by introducing LED lighting and/or individual lighting control of fluorescent lighting.
3. In adjustable lighting sessions of this study, LED lighting made the subjects feel that the typing task was easier than that under fluorescent lighting.
4. Compared to fluorescent lighting, LED lighting significantly reduced the lighting power consumption (by up to 65.5% in this study) without any negative impact on office task performances, subjective evaluations toward lighting quality or task satisfaction. Introduction of individual lighting control made the power saving higher and thus raised the lighting efficiency.

Note that these conclusions are applicable only within the scope of study. The light sources selected in this study were all UL certified cutting-edge lighting products, with CRI larger than 82. If light sources with lower CRI or narrowband spectral power distributions are used, Conclusion 1, the impact of light sources on color perception, might not be applicable. The CCT of the test room was 2902K – 3160K under LED lighting, 2802K – 3053K under fluorescent lighting. It depends on the CCT of the light sources and interior design of the test room. If the interior environment has changed, or if the CCTs of light sources are lower than 3000K, even though the CCT under LED lighting is still higher than that of fluorescent lighting, it may also cause uncomfortable feelings. Therefore, Conclusion 2, the impact of light sources on subjective feelings of CCT, is applicable only under the test environment of this study. Conclusion 3, the impact of light sources on typing task satisfaction also depends on the type of materials and subjects' visual acuity. In this study, the typing materials were presented in high contrast and the font size is 12 points. The visual acuities of subjects were 20/20 or better. If the typing materials are printed in smaller font size or in low contrast, or if the eyesight of office occupants is much lower, the typing task satisfaction may drop significantly even under LED lighting. Conclusion 4, the power consumption, depends on the efficiency of luminaires and the lighting control strategy. As discussed above, the light sources and luminaires were cutting-edge lighting products with high efficiency, and continuous individual lighting control was provided. If lower efficient luminaires are used or the lighting control method has changed, the power saving of 65.5% observed in this study may not be achieved. A complete list of the scope is listed in Table 5.1. Further investigations are needed if these conclusions are applied beyond the scope of this study.

Table 5.1 Research scope of this study

Item	Description	Notes
Light sources	Embedded LEDs and A-19 shaped LED lamp for LED lighting, fluorescent T8 linear lamps and compact fluorescent lamps for fluorescent lighting.	IV
CRI of light sources	>82, UL certified	Preset
Lighting control	with or without individual lighting control	IV
CCT of the test room	2902K – 3160K under LED lighting, 2802K – 3053K under fluorescent lighting.	Derived from DV
Font type of typing materials	Calibri, 12 points,	Preset
Color contrast of typing materials	black characters printed on white paper	Preset
Age of subjects	18-29	Preset
Snellen visual acuity of subjects	20/20, 20/16, 20/12.5	Preset
Color vision of subjects	Normal (self-declared)	Preset

5.2 Discussions

It was found that for fixed lighting without lighting control, the low CCT (around 3000K) of fluorescent lighting made subjects feel slightly warm. However, after introducing lighting control, the negative attitudes toward the low CCT were no longer presented, although the CCT remained unchanged. A possible reason could be that subjects were allowed to dim the fluorescent lighting to levels as they preferred, so they tended to have more confidence about the dimmed lighting condition, and paid less attention to the uncomfortable CCT. This is a tradeoff. This phenomenon was also found in a previous study showing that users had a more positive view of lighting installations with individual control (Moore 2004). This indicates that introduction of lighting control may enhance visual comfort and satisfaction. Also, this study found that CCT of 3000K or lower was generally considered slightly warm by office occupants. As currently there is no specific standard or guidance for selection of CCT for offices, this finding that 3000K is uncomfortably warm could be referred by office lighting designers.

There have been concerns in the lighting industry that the color rendering ability of LED is not as good as fluorescent lamps, since LED has relatively narrowband spectral power distributions compared to fluorescent lamps. There are also concerns that the correlation of CIE Color Rendering Index (CRI) is not suitable to describe the actual color rendering ability of LED (CIE 2007). Other metrics were developed to cope with this gap such as Philips CRI, NIST CQS, MCRI, etc. (Smet et al. 2010). The results of this study cleared all these concerns. In this study, the cutting-edge LED light sources as of 2012 have not only a good color rendering ability, but also a consistent color rendering performance throughout the process of dimming. Fluorescent light sources used in this

study, on the other hand, sacrificed the color rendering when dimmed, and caused reduction of performances of the task in which color discrimination was critical. The high color rendering performance was also proven correlated with the nominal high CIE CRI. This indicates that as the advance of LED technologies continue, it may not be necessary to worry about the color rendering performance of LEDs, but future studies are needed to prove this point.

Under controllable lighting, after replacing fluorescent lamps with LEDs, the subjective feeling of typing task difficulty decreased but there was no improvement in task performance. This phenomenon is consistent with previous findings that satisfactions were not associated with cognitive task performance (Veitch and Gifford 1996). However, it is still unclear why LED lighting improved the task satisfaction of typing tasks, while LED did not have any significant effect on the task satisfaction or color matching task satisfaction. This indicates that the cause may not be relevant to the chromatic features of LED. The improvement of task satisfactions might be caused by other factors, for example, the luminous contrast between task and background. The results of HDR photography are expected to reveal the real cause.

Unfortunately, due to the limitation of time and resources, the data fusion of HDR photography had not been completed when this thesis was finished. A future analysis of the fused HDR images is needed.

This study has many contributions to the lighting society. First, this study proved the feasibility and advantage of LED in office lighting, with better color perception, better subjective attitudes toward lighting quality, and better typing task satisfaction, than fluorescent lighting. Second, as discussed above, this study proved that good color

perception can be achieved in offices with cutting-edge LED technology. Third, as the CCT of 3000K and lower was generally considered slight warmer in the experiments, this study provided references for the selection of CCT in offices.

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APPENDIX A A Complete List of Questions in the Questionnaire

Questions	Question type
Lighting quality survey:	
<i>(Light level related)</i>	
1. The lighting is uncomfortably bright for the tasks that I perform.	agree/disagree
2. The lighting is uncomfortably dim for the tasks that I perform.	agree/disagree
<i>(light distribution related)</i>	
3. The lighting is poorly distributed with unacceptable non-uniformity	agree/disagree
4. The lighting causes undesired deep shadows	agree/disagree
5. The contrast between the task and background is too strong and uncomfortable	agree/disagree
<i>(glare related)</i>	
6. Reflections from the light fixtures hinder my work.	agree/disagree
7. The light fixtures are too bright.	agree/disagree
<i>(CRI related)</i>	
8. My skin is an unnatural tone under the lighting.	agree/disagree
9. Colored objects in the room look unreal or less legible	agree/disagree
<i>(CCT related)</i>	
10. The lighting is too warm for me or my work	agree/disagree
11. The lighting is too cold for me or my work	agree/disagree
12. The lighting color temperature is just fine for me or my work	agree/disagree
<i>(other physical factors)</i>	
13. The lights flicker throughout the test.	agree/disagree
14. There is an unwanted humming noise of the lighting system	agree/disagree
<i>(overall attitudes)</i>	
15. Overall, the lighting is comfortable.	agree/disagree
16. Overall, lighting in the office environment is acceptable	agree/disagree
17. Overall, I like to live and work in this office lighting environment	agree/disagree
Task satisfactions:	
18. How do you rate the difficulty of the typing task you did?	5-scale, 0 ~ 4

(0 means easiest, 4 means hardest)

19. How do you rate your satisfaction with your typing task performance? 5-scale, 0 ~ 4

(0 means the least satisfied, 4 means the most satisfied)

20. How do you rate the difficulty of the color matching task you did? 5-scale, 0 ~ 4
(0 means easiest, 4 means hardest)

21. How do you rate your satisfaction with your color matching task performance? (0 means the least satisfied, 4 means the most satisfied) 5-scale, 0 ~ 4

APPENDIX B Philips Perform fluorescent luminaire cut-sheet

application

- Economical architectural recessed direct/indirect lighting for glare free illumination.
- Suitable for grid inverted T (NEMA "G") ceilings. Flange type ceilings (NEMA "F") require independently mounted flange kits (FMA).
- Screw slot (NEMA "SS") ceiling models are designed to position the bottom of the luminaire at the ceiling plane.

• Fully recessed mounting, suitable for row mounting.

construction/finish

- Welded housing construction.
- Soft white baked enamel finish.
- Easy ballast access through lamp compartment.
- Grid clips included.

electrical

- Class P,HPF ballasts comply with © Federal Ballast Law (Public Law 100-357, 1988).
- UL listed for damp locations. Canadian listing optional.
- Self-contained fluorescent emergency power pack can be incorporated. Some models will require a ballast box on top of the luminaire.

enclosures

- Micro-perforated mesh lamp shield provides soft awareness of light source.
- Soft white overlay on inside of micro-perforated mesh conceals lamp image and balances between reflected and direct light.
- Swing down lamp shield for easy relamping.

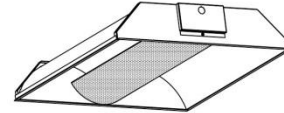
accessories

- **FMA22** – 2' x 2' "F" mounting frame for NEMA "F" mounting.

0507.2-AR

Architectural Fluorescent

PerForm
Recessed Direct/Indirect
2x2 1, 2, or 3 lamp
T5, T5HO, T8, or CFTT5



Specifier's Reference

Project
Type
Model No.
Comments

Green Choice: 2PFG217-PMW-UNV-1/2-EBHE-LPT835HL

2	PF	G	3	17	-	PMW	-	120	-	1/3-EBD
Width 2 - 2'		Ceiling Type G - Grid T - Screw Slot		Lamp Type/Wattage 14 - 14W T5 (22") 17 - 17W T8 (24") 24HO - 24W T5HO (22") CF40 - 40W T5 (24") CF50 - 50W T5 (24") CF55 - 55W T5 (24")				Voltage 120 277 347 UNV - Universal voltage, 120-277 volt.		
	Family PF - PerForm		No. of Lamps (not included) 1 2 3 (except CF)			Shielding PMW - Perforated metal with white overlay				Options 1/1 - One 1-lamp ballast (electronic or non-standard) 1/2 - One 2-lamp ballast (electronic or non-standard) 1/3 - One 3-lamp ballast (electronic or non-standard) 1/21 - 2-lamp & 1-lamp ballasts (electronic or non-standard) CM - Canadian Market EB - Electronic ballast, <20% THD EB101 - Electronic ballast, instant start, <10% THD EB10R - Electronic ballast, program rapid start, <10% THD EBD - Electronic dimming ballast EBHE - T8 electronic ballast, high efficiency, std. ballast factor EBLHE - T8 electronic ballast, high efficiency, low ballast factor EBHHE - T8 electronic ballast, high efficiency, high ballast factor E1 - DEB-1 emerg. ballast (T8 or CF only), 350-450 lumens (UL dry loc.) E7 - DEB-7 emerg. ballast, 390-700 lumens (UL dry loc.) E5 - DEB-5 emerg. ballast (T8 or CF only), 1100-1400 lumens (UL dry loc.) ESST - DEB-SST emerg. ballast with self test, 1100-1400 lumens (UL dry loc.) F1 - Installed flex, 3/8" diameter, 18 gauge, 3 wire, 6' F2 - Installed flex, 3/8" diameter, 18 gauge, 4 wire, 6' GLR# - Fusing, fast blow (# = number of ballasts) LPT735 - Installed T8 lamps, 70+ CRI, 3500K LPT835 - Installed T5/T5HO/T8/CF lamps, 80+ CRI, 3500K LPT835HL - Installed T8 or T5 hi lumen lamps, 80+ CRI, 3500K

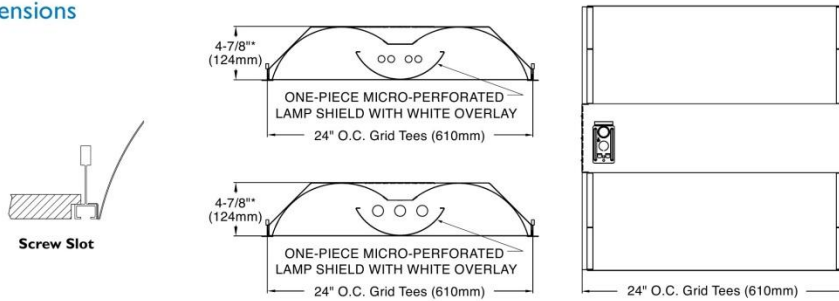
Job pack stretch wrapped w/out cartons - see sheet 1603-OA.
See section 1600-OA for ballast, lamp, and option information.

PHILIPS
Day-Brite

0507.2-AR

PerForm 2x2 1, 2, or 3 lamp T5, T5HO, T8, or CFTT5 Recessed Direct/Indirect

dimensions



*Models with emergency ballast may require a ballast box on top of luminaire.

photometry

PerForm 2x2 2 Lamp CF40

Efficiency – 69.6%

LER – 59

TER – 51

Catalog No.		Candlepower				Light Distribution				Average Luminance			
Test No.	S/MH	Angle	End	45	Cross	Degrees	Lumens	% Lamp	% Luminaire	Angle	End	45°	Cross
2PFG2CF40-PMW-1/2-EB	26755	0	1545	1545	1545	0-30	1202	19.1	27.4	45	3623	3981	4274
40WTT5	3150	5	1538	1536	1538	0-40	1972	31.3	45.0	55	3228	3852	4265
0.88	0.88	10	1513	1515	1522	0-60	3495	55.5	79.7	65	2713	3598	4043
65	65	15	1474	1482	1496	0-90	4385	69.6	100.0	75	2152	2901	2974
		20	1419	1439	1460					85	1359	1729	2038
		25	1352	1382	1412								
		30	1270	1313	1355								
		35	1173	1233	1289								
		40	1068	1145	1212								
		45	952	1046	1123								
		50	818	936	1020								
		55	688	821	909								
		60	551	699	781								
		65	426	565	635								
		70	308	428	465								
		75	207	279	286								
		80	117	139	168								
		85	44	56	66								

Comparative yearly lighting energy cost per 1000 lumens – \$4.07 based on 3000 hrs. and \$.08 pwr KWH.

The photometric results were obtained in the Philips Day-Brite laboratory which is NVLAP accredited by the National Institute of Standards and Technology.

PerForm 2x2 3 Lamp T8

Efficiency – 61.7%

LER – 42

TER – 36

Catalog No.		Candlepower				Light Distribution				Average Luminance			
Test No.	S/MH	Angle	End	45	Cross	Degrees	Lumens	% Lamp	% Luminaire	Angle	End	45°	Cross
2PFG317-PMW-1/3-EB	26746	0	852	852	852	0-30	665	16.7	27.1	45	2032	2215	2401
F17T8	1325	5	848	846	848	0-40	1093	27.5	44.5	55	1820	2172	2430
0.88	0.88	10	837	836	839	0-60	1950	49.0	79.5	65	1528	2063	2324
51	51	15	816	818	826	0-90	2453	61.7	100.0	75	1206	1622	1632
		20	787	794	806					85	803	926	1081
		25	752	764	782								
		30	708	726	750								
		35	657	683	715								
		40	598	635	675								
		45	534	582	631								
		50	463	523	578								
		55	388	463	518								
		60	312	396	450								
		65	240	324	365								
		70	173	246	261								
		75	116	156	157								
		80	66	78	95								
		85	26	30	35								

Comparative yearly lighting energy cost per 1000 lumens – \$5.71 based on 3000 hrs. and \$.08 pwr KWH.

The photometric results were obtained in the Philips Day-Brite laboratory which is NVLAP accredited by the National Institute of Standards and Technology.

Additional test numbers available on-line.



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776 South Green Street • Tupelo, MS 38804
p. 800.234.1890 • f. 662.841.5501
Canadian Division
189 Bullock Drive • Markham, Ontario L3P 1W4
p. 905.294.9570 • f. 905.294.9811

Contact Factory for Additional Configurations.
Specifications are subject to change without notice.



Some luminaires use fluorescent or high intensity discharge (HID) lamps that contain small amounts of mercury. Such lamps are labeled, "Contain Mercury" and/or the symbol "HG". Lamps that contain mercury must be disposed of in accordance with local requirements. Information regarding lamp recycling and disposal can be found at www.lamprecycle.org

APPENDIX C Cree CR22 LED luminaire cut-sheet

CR22™

2'x2' Architectural LED Troffer

Product Description

The CR22™ architectural LED troffer delivers up to 3200 lumens of exceptional 90+ CRI light while achieving 90 lumens per watt. This breakthrough performance is achieved by combining the high efficacy and high-quality light of Cree TrueWhite® Technology with a unique thermal management approach. The CR22 is available in neutral or cool color temperatures and has step, 0-10V, or Lutron EcoSystem® Enabled dimming options. Its compact, lightweight design easily accommodates recessed, surface mount, or suspended installations, making the CR22 perfect for use in commercial new construction or retrofit applications.

Performance Summary

Utilizes Cree TrueWhite® Technology

Active Color Management

Room-Side Heat Sink

Made in America

Efficacy: 90 LPW

Delivered Light Output: 2000, 3200 lumens

Input Power: 22, 35 watts

CRI: 90

CCT: 3000K, 3500K, 4000K

Input Voltage: 120-277 VAC

Warranty: 10 Years*

Lifetime: Designed to last 50,000 hours

Controls: Step Level to 50%, 0-10V Dimming or Lutron EcoSystem® Enabled to 5%¹

Mounting: Recessed

Dimensions: L 23.7" x W 23.7" x H 4.75"

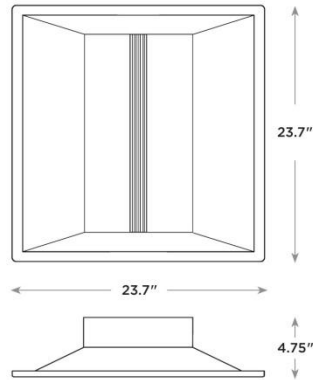
Weight: max 20lbs.

Housings & Accessories

Reference Housing & Accessory documents for more details.

Accessories	
SMK-CR22³ Surface Mount Kit	CPLCR Chicago Plenum Field Kit
DGA22-WHT Drywall Grid Adaptor-White	CPLCR-EM Chicago Plenum Field Kit-Emergency
EJBCR-5PK Expanded size junction box for through wiring (5 pack)	

CR22



NOTE: Use of Expanded Junction Box will expand the depth to 6.67" and Emergency Backup will expand the depth to 6.30".

Ordering Information

Example: CR22-20L-35K-S

CR22					
Product	Lumen Output	Color Temperature	Voltage	Control	Options
CR22	20L 22W 2000 lumens - 90 LPW 32L 35W 3200 lumens - 90 LPW	30K 3000 Kelvin 35K 3500 Kelvin 40K 4000 Kelvin	Blank 120-277 Volt (Standard)	S Step Dimming to 50% 10V 0-10V Dimming to 5% LES Lutron EcoSystem® Enabled to 5%	EB14² Emergency Backup - 1400 lumens EB14 SMK^{2,4} Emergency Backup with surface mount kit - 1400 lumens

1. Reference www.cree.com/lighting for recommended dimming control options. 2. Not available with 50L or LES option. 3. Not available with EB14 option. Use EB14 SMK. 4. Includes surface mount kit accessory (SMK-CR24). Suggested MSRP for the adder over the standard CR Series fixture for the Lutron EcoSystem® Enabled feature is \$49. ⁵See www.cree.com/lighting for warranty terms.



Rev. Date 11/21/2012



www.cree.com/lighting

T (800) 236-6800 F (262) 504-5415

www.cree.com/canada

T (800) 473-1234 F (800) 890-7507

CR22™

Product Specifications

CREE TRUEWHITE TECHNOLOGY

A revolutionary way to generate high-quality white light, Cree TrueWhite® Technology mixes the light from the highest performing red and unsaturated yellow LEDs. This patented approach delivers an exclusive combination of 90+ CRI, beautiful light characteristics, and lifelong color consistency, all while maintaining high luminous efficacy—a true no compromise solution.

ROOM-SIDE HEAT SINK

An innovative thermal management system designed to maximize cooling effectiveness by integrating a unique room-side heat sink into the diffusing lens. This breakthrough design creates a pleasing architectural aesthetic while conducting heat away from LEDs in a temperature-controlled environment. This enables the LEDs to consistently run cooler, providing significant boosts to lifetime, efficacy, and color consistency.

LUMEN MAINTENANCE FACTORS

- Reference www.cree.com/lighting for detailed lumen maintenance factors.

CONSTRUCTION & MATERIALS

- Durable 20-gauge steel housing with standard troffer access plate for electrical installation.
- Field replaceable light engine integrates LEDs, driver, power supply, thermal management, and optical mixing components.
- One-piece lower reflector finished with a textured high reflectance white polyester powder coating creates a comfortable visual transition from the lens to the ceiling plane.
- Provided t-bar clips and holes for mounting support wires enable recessed or suspended installation.
- Individual fixtures may be mounted end to end for a continuous row of illumination.

NOTE: Reference www.cree.com/lighting for detailed instructions on field replacement of the light engine.

OPTICAL SYSTEM

- Unique combination of reflective and refractive optical components achieves a uniform, comfortable appearance while eliminating pixelation and color fringing.
- Components work together to optimize distribution, balancing the delivery of high illuminance levels on horizontal surfaces with an ideal amount of light on walls and vertical surfaces. This increases the perception of spaciousness.
- Diffusing lens integrated with upward-facing LED strip eliminates direct view of LEDs while lower reflector balances brightness of lens with the ceiling to create a low-glare high angle appearance.

ELECTRICAL SYSTEM

- Integral, high-efficiency driver and power supply.
- **Power Factor** = 0.9 nominal
- **Input Power:** Stays constant over life.
- **Input Voltage:** 120V-277V, 50/60Hz
- **Battery Backup:** Consult factory.
- **Temperature Rating:** Designed to operate in temperatures 35 C and below room side and plenum side.
- **Total Harmonic Distortion:** < 20%

CONTROLS

- Step dimming to 50% comes standard.*
- Optional continuous dimming to 5% with 0-10V DC control protocol.*
- Optional Lutron EcoSystem® Enabled option allows seamless integration with Lutron EcoSystem controls.*

REGULATORY & VOLUNTARY QUALIFICATIONS

- UL924 (EBI4 option).
- cULus Listed.
- DLC qualified.**
- Suitable for damp locations.

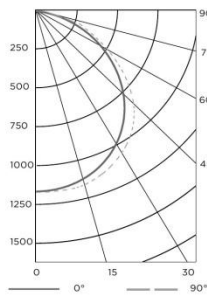
*Reference www.cree.com/lighting for recommended dimming controls and wiring diagrams.
**Does not apply to -LES models.

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www.cree.com/lighting T (800) 236-6800 F (262) 504-5415

Photometry

CR22 BASED ON LTL REPORT TEST #: 24292



Coefficients Of Utilization

RCC %:	80			
RW %:	70	50	30	10
RCR: 0	119	119	119	119
1	110	105	101	98
2	100	92	85	80
3	91	81	73	67
4	84	72	63	57
5	77	64	55	49
6	71	58	49	43
7	66	52	44	38
8	61	48	39	33
9	57	44	36	30
10	53	40	32	27

Effective Floor Cavity Reflectance: 20%

Average Luminance Table (cd/m2)

Vertical Angle	Horizontal Angle		
	0°	45°	90°
0°	3864	3864	3864
45°	3575	3864	3972
55°	3164	3656	3758
65°	2498	3133	3347
75°	1620	2348	2051
85°	366	252	168

Zonal Lumen Summary

Zone	Lumens	% Lamp	Luminaire
0-30	923	N/A	28.1%
0-40	1527	N/A	46.5%
0-60	2704	N/A	82.5%
0-90	3280	N/A	100%

Reference www.cree.com/lighting for detailed photometric data.

Application Reference

Spacing	Open Space				
	Lumens	Wattage	LPW	w/ft²	Average fc
8 x 8	2000L	22W	90	0.35	28
	3200L	35W	90	0.55	44
8 x 10	2000L	22W	90	0.28	23
	3200L	35W	90	0.44	37
10 x 10	2000L	22W	90	0.22	20
	3200L	35W	90	0.35	31
10 x 12	2000L	22W	90	0.19	16
	3200L	35W	90	0.29	25

9' ceiling; 80/50/20 reflectances; 2.5' workplane, open room LLF: 1.0 Initial. Open Space: 50' x 40' x 10'



www.cree.com/canada T (800) 473-1234 F (800) 890-7507

APPENDIX D Philips Award Winning LED lamp cut-sheet



Award Winning LED Bulb

10A19/LPRIZE-PRO/2700-900 DIM 10/1

Philips Award Winning LED Bulb is the efficient, LED alternative to a standard 60 watt incandescent A19 bulb with 800 lumens. The unique bulb design provides omni-directional light with only 10 watts of power.

Product data

• General Characteristics

Cap-Base	E26
Bulb	A19
Bulb Finish	- [-]
Rated Avg. Life (Hours)	30000 hr
Rated Avg. Life (Hours)	30000 hr

• Light Technical Characteristics

Color Code	WW
Color Designation	Warm White
Beam Angle	0 D
Correlated Color Temperature	2700 K
Approximate Lumens	900 Lm
CRI	90
Color Temp. (Kelvin)	2700 K [CCT 2700K]
Rated Luminous Flux	900 Lm

• Electrical Characteristics

Wattage	10 W
Wattage Technical	10.0 W

Voltage	120 V
Dimmable	Yes

• Product Dimensions

Overall Length C	122 mm
Overall Length C [inch]	4.807 (max) in
Diameter D	69 mm

• Product Data

Product number	420224
Full product name	10A19/LPRIZE-PRO/2700-900 DIM 10/1
Short product name	10A19/LPRIZE-PRO/2700-900 DIM 10/1
Pieces per Sku	1
eop_pck_cfg	6
Skus/Case	6
Bar code on pack	46677420222
Bar code on case	50046677420227
Logistics code(s)	929000209704
eop_net_weight_pp	0.120 kg

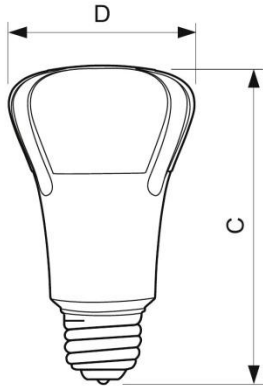
Dimensional drawing



PHILIPS
sense and simplicity

Award Winning LED Bulb

Dimensional drawing



10A19/LPRIZE-PRO/2700-900 DIM 10/1

Product	C (Norm)	C1 (Max)	D (Norm)	D1 (Norm)
LED 10W E26 2700K 120V A19 DIM	122	4.807	69	2.719



E26



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www.philips.com/lighting

2012, December 1
data subject to change

APPENDIX E Lutron DIVA wall dimmer cut-sheet

Diva®

0-10V Control

Wallbox Controls

369-147 1 08.12.09

Diva® 0-10V Control

The designer dimmer that matches your paddle switches.

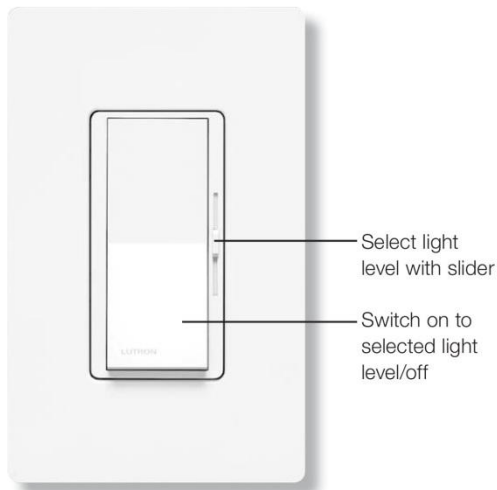
Features

- Large paddle switch with a captive linear-slide dimmer for a standard designer wallplate opening.
- Uses low-voltage wiring for easy installation in any home.
- Coordinating Claro® and Satin Colors® wallplates. (available separately)
- High-end and low-end trim user adjustable for optimal performance.

Available Model Numbers:




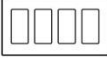
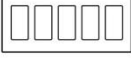
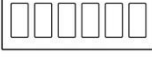
DDTV-XX - Gloss Finish

DVSCTV-XX - *Satin Colors*



The *Diva* 0-10V preset dimmer provides dimming control of 0-10V LED drivers, fluorescent ballasts and HID ballasts.

Standard Wallplates

	1-Gang CW-1-, SC-1- 2.94 in W (75 mm) x 4.69 in H (119 mm) x 0.30"D (7.6 mm)
	2-Gang CW-2-, SC-2- 4.75 in W (121 mm) x 4.69 in H (119 mm) x 0.30 in D (7.6 mm)
	3-Gang CW-3-, SC-3- 6.56 in W (167 mm) x 4.69 in H (119 mm) x 0.30 in D (7.6 mm)
	4-Gang CW-4-, SC-4- 8.37 in W (213 mm) x 4.69 in H (119 mm) x 0.30 in D (7.6 mm)
	5-Gang CW-5-, SC-5- 10.18 in W (259 mm) x 4.69 in H (119 mm) x 0.30 in D (7.6 mm)
	6-Gang CW-6-, SC-6- 12.00 in W (305 mm) x 4.69 in H (119 mm) x 0.30 in D (7.6 mm)

 **LUTRON**. SPECIFICATION SUBMITTAL

Page 1

Job Name: <input style="width: 90%;" type="text"/>	Model Numbers: <input style="width: 95%;" type="text"/>
Job Number: <input style="width: 80%;" type="text"/>	<input style="width: 45%;" type="text"/> <input style="width: 45%;" type="text"/>

Specifications

Power

- **Control:** 0-10 V \approx 30 mA
- **Switch:** 24 V \approx 100 mA

Performance

- Power-failure memory.
- Electrostatic discharge tested.

Environment

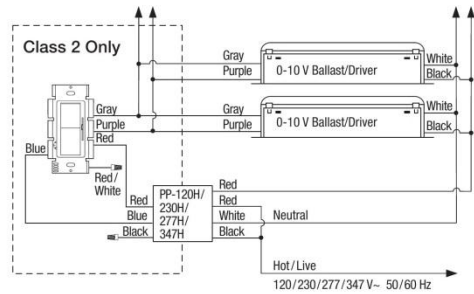
- For Indoor Use Only.
- Operating Temperatures 0 °C (32 °F) to 40 °C (104 °F).

Application Requirements

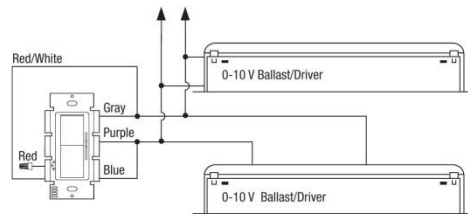
- No derating required if ganged.
- A physical barrier (partition) must exist when ganging with line-voltage products.
- Precise color matching.
- Night Light not available.
- Provides 0-10V sinking control for 0-10V fluorescent ballasts and LED drivers.
- Compatible with all fluorescent ballasts and LED drivers compliant to IEC 60929 Annex E.2.

Wiring Diagrams

Dimming With ON/OFF Control
Wiring Diagram Using Relay

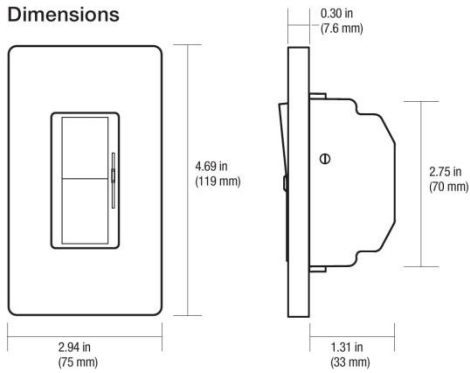


Dimming With ON/OFF Control For Drivers Which Support
Dim To OFF Capability
Power Wiring Not Shown—See Lighting Device For Wiring



Job Name:	Model Numbers:	
<input type="text"/>	<input type="text"/>	<input type="text"/>
Job Number:	<input type="text"/>	<input type="text"/>

Dimensions



Standard Colors and Finishes

Gloss Finishes

Add color suffix to model # **Example: DVTV-WH**

- WH White
- IV Ivory
- AL Almond
- LA Light Almond
- GR Gray
- BR Brown
- BL Black

Satin Colors®

Add color suffix to model # **Example: DVSCTV-SW**

- HT Hot
- MR Merlot
- PL Plum
- TQ Turquoise
- SG Sea Glass
- TP Taupe
- ES Eggshell
- BI Biscuit
- SW Snow
- PD Palladium
- MN Midnight
- TC Terracotta
- SI Sienna
- GB Green Briar
- BG Bluestone
- MS Mocha Stone
- GS Goldstone
- DS Desert Stone
- ST Stone
- LS Limestone

Job Name: <input style="width: 90%;" type="text"/>	Model Numbers: <input style="width: 60%;" type="text"/> <input style="width: 40%;" type="text"/>	
Job Number: <input style="width: 80%;" type="text"/>	<input style="width: 30%;" type="text"/>	<input style="width: 70%;" type="text"/>

APPENDIX F Lutron Credenza CFL/LED dimmer cut-sheet

Lamp dimmers | Credenza® and Attaché®



Shown actual size: Credenza lamp dimmer in White (WH).

Credenza lamp dimmer dimensions are 1.5 in (38 mm) x 3.10 in (79 mm).

Available finishes

Use **BOLD** color code in model number (Example: TT-300NLH-**BR**)

Gloss finishes



WH
White



BR
Brown

BL
Black
(Credenza only)

Product family features

- Convenient full range dimmers for table and floor lamps
- Use a standard light bulb instead of costly 3-level bulbs
- **C•L™** dimmers offer more reliable dimming performance over standard dimmers when dimming CFLs and LED. They also provide full range dimming for incandescent and halogen bulbs as well as mixed loads types.
- LED glows softly as a locator light (optional feature)
- Place Credenza dimmer on tabletop or connect the Attaché dimmer to the lamp cord
- For detailed information, see Application Notes #91 (Guide to Dimming Table Lamps) by visiting www.lutron.com/applicationnotes
- Cord is 6 ft (1.8m) long

Direct load type compatibility

-  Incandescent/halogen lighting
-  Dimmable CFL/LED lighting (screw-base)

Plug-in lamp dimmers are also available for:



Maestro Wireless®
See pg. 70



Spacer System® IR
See pg. 78