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Evaluating and Designing Light-emitting Diode Desk Lamps for Writing and Drawing

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***Abstract*—This study investigated the subjective visual fatigue and objective blink rates of users who use light-emitting diode (LED) desk lamps for writing and drawing, thereby identifying the optimal design parameters for LED lamps. First, a dark room with no interfering light sources was designed according to the factors of LED array, color temperature, and diffuser haze, with each factor in turn comprising three standards. Specifically, the LED arrays of the point sources were divided into high density (d = 2cm), medium density (√2d), and low density (2d). The color temperatures of the light sources were divided into warm (2700 K), neutral (4000 K), and cool (6500 K). Finally, the diffuser haze settings were divided into no diffuser, medium haze (50%), and high haze (90%). The number of experimental groups was simplified to nine according to a Taguchi orthogonal array. To determine the amount of fatigue experienced by the participants, the participants wrote and drew under the nine selected desk lamp models and filled out the subjective fatigue scales; in addition, the objective blink rates of the participants were measured. Signal-to-noise ratios were employed for factor analysis. The results of the subjective fatigue scale and the objective blink rates both indicated that low-density arrays, warm colors, and nondiffuser settings were unsuitable design parameters for LED lamps devised for writing and drawing. Finally, the subjective and objective analysis results were compared to provide a reference for LED product designers.**

***Keywords*—LED Desk Lamp Design; Taguchi Method; Visual Assessment**

I. INTRODUCTION

Since their invention, light-emitting diodes (LEDs) have been widely considered the lighting technology of the future because of their low power consumption and long lifespans (Harris, 2009). The development of blue-light LEDs has caused the unit prices of high-performance LEDs to decrease, with high-performance LEDs being increasingly used in lighting such as electric and fluorescent lights (Sommer et. al., 2010). According to Jackson (2012), the percentage of lighting areas that use LEDs could exceed 40% by 2020.

Numerous countries are actively promoting the LED industry, with using LEDs as energy-saving lighting progressively becoming an international trend (Akasaki et al., 2014). In addition, compared with energy-saving light bulbs, LED lighting causes less concern regarding mercury pollution and overall environmental damage. Therefore, LEDs have become the most prevalent green lighting product in recent years.

The effect of lighting on visual health must be considered. Lighting should not flicker, illuminate unstably, or cause hazardous radiation such as ultraviolet or infrared radiation; reading and working under this type of lighting environment for a prolonged period may cause subsequent visual fatigue, loss, or even permanent visual damage. LEDs fulfill the aforementioned conditions in that they neither flicker nor contain ultraviolet or infrared in their spectrum, thus generating no hazardous radiation. Consequently, LEDs do not affect human eyes negatively (Crawford, 2009). Therefore, the development, design, and application of LED lighting have been regarded topics with high research and development potential (Yam and Hassan, 2005). LEDs will play an indispensable role in the future of the lighting industry.

The structure of LED light exhibits high directivity; designing such high-intensity lighting requires paying special attention to visual discomfort (Sammarco et al., 2010). Single LED light sources currently faces difficulties in heat dispersion. However, creating a module that employs multiple LED sources enables high mobility and heat dispersion (Crawford, 2005). LEDs employ point-source lighting. However, when a person writes or draws under an unevenly distributed light, a multishadow effect is produced on the paper or drawing surface because of reflections caused by the pen and hand, thus disturbing the person's eye focus and producing visual fatigue (Chiang et al., 2015). Previous studies on LED lighting designs have focused primarily on models for reading (Huang et al., 2013; Vienot et al., 2009; Islam et al., 2015; Narendran and Deng, 2002).

However, because reading does not involve the action of pens or the hands, multishadows cause little effect on people using desk lamps for reading. Therefore, writing and drawing require a different model of desk lamp than reading does. This study analyzed desk lamps for writing and drawing.

First, on the basis that each LED bulb in a desk lamp was a point source, the study investigated two scenarios: when the LED pitch was longer than the size of the illuminated object and when it was shorter (Chiang et al., 2015). In these scenarios, each point source formed a single shadow. When two point sources are used simultaneously, parts of the two shadows overlap and form a double shadow. When three or more point sources are used simultaneously, the shadow becomes a more complex multishadow. Wu et al. (2011) indicated that greater LED pitches cause greater, nonoverlapping areas. Therefore, the shadow-overlapping effect of an LED desk lamp is influenced by its LED pitches. Numerous studies have been conducted on LED array (Moreno et al., 2006; Qin et al., 2012). Secondly, a diffuser is used to even the illumination from LED point sources. Numerous studies have been conducted on diffuser designs (Chien et al. 2007; Chang et al., 2006; Pan et al., 2011). The diffuser is a type of optical film that diffuses the light passing through its chemical coating, thereby forming relatively even light. Manufacturers of diffusers must consider its material thickness, transmittance, and haze. Particularly, haze greatly influences diffuser design (Kuo et al., 2009; Tsuei et al., 2008). Haze is generated when an even light source passes through a transparent and rough object, thereby dividing the incidental light into transmitted and scattered light. Haze is calculated to be the optical ratio of the scattered light to the incident light and is expressed typically as a percentage. Selecting the size of a diffuser requires examining the optical requirements of the backlight module because high haze evens surface light more substantially. Furthermore, the International Commission on Illumination (Commission internationale de l'éclairage, CIE) categorizes indoor lighting into three types of color temperature: warm (<3300 K), neutral (3300-5000 K), and cool (>5000 K). Numerous studies have reported that color temperature is a key factor that shapes environments and affects the physical and psychological well-being of people in those environments (Wohlfarth and Gates, 1985), as well as their work efficiency. Hawes et al. (2012) and Baron and Thomley (1994) have addressed the effect of the color temperature of industrial LEDs on perception, cognition, and affective states. Therefore, color temperature was included as one of the factors affecting visual fatigue in this study.

Assessments of whether LED desk lamps cause eye fatigue in people who are writing and drawing can be categorized into subjective and objective types. According to Sinclair (1990), subjective assessments comprise five types of methods: ranking, rating, questionnaire, interview, and checklist methods. In particular, the questionnaire method is the most prevalently applied. Subjective fatigue assessment is easy to perform and relatively inexpensive. In investigating the correlation between the subjective visual fatigue of participants and the actual fatigue symptoms, Yoshitake (1971) reported the correlation coefficient to be at least 0.8. Therefore, subjective assessments are feasible for evaluating the severity of visual fatigue (Blackwell, 1997; Kim et al., 2008). In addition, numerous scholars have indicated that changes in blinking behaviors are related to discomfort. In a 4-hour driving simulation experiment, Haider and Rohmert (1976) reported that the blink rates of the participants increased between 80% and 100%. In exploring the changes in the blink rates of the nine participants of a 14-hour continuous vigilance operation, French et al. (1992) reported that the blinking rate increased from an initial 27 times per minute to 37 times per minutes by the end of the experiment. In a similar study on the blinking behaviors of drivers, Benedetto et al. (2011) examined the correlation between blink rates and blink duration. In this study, the blinking frequency of each participant during the experiment was recorded, and the blink rates were evaluated as an objective basis for evaluating the severity of the visual discomfort of the participants.

In summary, this study examined three factors of LED desk lamps: color temperature, LED array, and diffuser haze. Each factor was influenced by multiple standards; establishing a desk lamp model and an experiment for each of the factors was time-consuming and costly. Taguchi (1986) developed the Taguchi method of experiment planning, which involves minimizing experiment combinations, costs, and time while achieving maximal quality results. Orthogonal arrays and signal-to-noise (S/N) ratios emphasize maximizing product quality and production designs while minimizing the variance in product performance (Park, 1996). Roy (2001) indicated that the Taguchi method involves using a standardized comparison chart, referred to as an orthogonal array, to establish an experiment design. In parameter design, the S/N ratio is calculated to formulate optimal factor-standard combinations. The S/N ratio is an assessment index involving the mean and the variance simultaneously; the greater the ratio is, the smaller the variance in quality and the higher the product quality.

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Therefore, this study used the Taguchi method to investigate the effect of LED desk lamps for writing and drawing on visual fatigue in users. In the experiment, subjective fatigue scales and objective blink rates were used to identify the optimal combination of color temperature, LED array, and diffuser haze, thereby providing a reference to possible visual fatigue in users for the consumer use and lighting design of LED desk lamps for writing and drawing.

II. METHODS

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A. Participants

There were a total of two pretest participants (one man and one woman) and 15 experiment participants (eight men and seven women) in the formal experiment. The rectified visual acuity of the participants was .8 or higher according to Snellen's E chart. All of the participants were 20-30 years old, not color-blind or color-weak observers, and experienced in design illustration.

B. Experiment Framework

Figure 1 illustrates the experiment framework comprising the environmental setting, an LED desk lamp, and a blink rate recorder.

The experiment was performed in a 5 × 4 × 2.5 m space that included a 150 × 80 × 73 cm table and a chair with 38 × 38 × 45 cm chair surface. To reduce the multi-shadow effect caused by the environmental lighting on the experiment data, the spatial design was maintained to be light pollution-free. To minimize the effect of the ambient temperature and humidity on the participants, the ambient temperature and humidity were maintained at 26 °C and 60%, respectively, and the vent of the air conditioner was adjusted away from the participants to prevent the sensation of dry eyes. The sitting position and test distance of the two pretest participants (between the desk and the participant's eyes) were first measured according to Shieh and Lin (2000). The distance was maintained at 42.3 cm, and the desk lamp was positioned 40 cm above the desk surface, thereby ensuring that the participants' eyes did not experience intense glare caused by direct light.

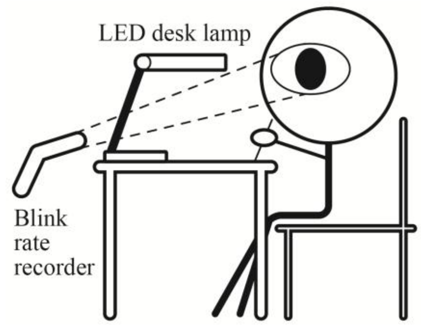

Figure 1 Research Framework

Figure 2 depicts the structural diagram of the LED desk lamp, which was modified according to a 3M Polarizing LED desk lamp. The LED panel and diffuser were modified as they are the primary experimental variables. Specifically, this experiment involved three types of diffuser settings: no diffuser, a 50%-haze diffuser, and a 90%-haze diffuser. This experiment used MU06 (50% haze) and MU08 (90% haze) diffusers, which were developed by the JC Lambda Light Material Corp and featured a 120-µm thickness and a 94% transmittance.

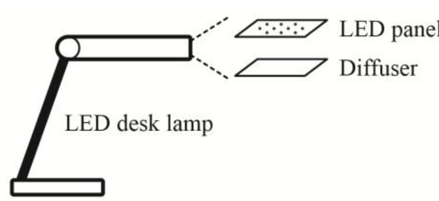

Figure 2 Structural Diagram Of The LED Desk Lamp

The LED panel design primarily concerned the color temperature and LED array. To enable the lamp generate various color temperatures, three LED bulbs with varying color temperatures were embedded at each point source. These bulbs were LED bulbs of high color-rendering properties (Ra > 80), of 5700 K (CIE x = .3294, CIE y = .3475), 4000 K (CIE x = .3783, CIE y = .3765), and 2700 K (CIE x = .4578, CIE y = .4076). The LED arrays are shown in Figure 3. When D, E, H, and I were lit, the LED pitch was d (2cm); when B, F, G, and K were lit, the LED pitch was √2d; when A, C, J, and L were lit, the LED pitch was 2d. The pitches were designed to focus the central brightness of each set of four lit LED points at the same spot.

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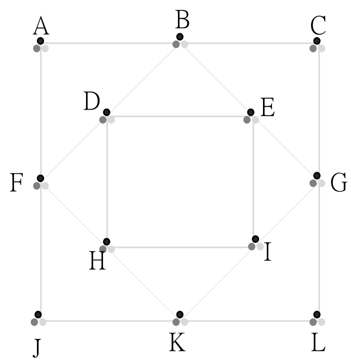

Figure 3 Array Of The LED Panel

The blink rate recorder recorded the eyes of the participants with a Sony HD recorder and transmitted the results into the computer for calculating the blink rate.

C. Experiment Planning

Orthogonal arrays are used to configure control and noise factors in experiments according to product reproducibility, durability, and cost, thereby simplifying the planning for tests that involve numerous factors or combinations of standards. Park (1996) determined that orthogonal scales are the basis for experiment designs that employ the Taguchi method. Orthogonal arrays are employed to establish standard value arrays comprising groups of orthogonal vector lines. Parameter designs incorporate the calculation of S/N ratios to create optimal factor-standard combinations. S/N ratios are a type of assessment index involving means and variances simultaneously; the greater an S/N ratio is, the smaller the variance in quality and the higher the product quality. In this study, the results of the questionnaire on subjective fatigue and the objective blink rate were considered as the smaller the better (STB). Because of the STB characteristics, the ideal target value was zero and was thus the quality loss function for the individual products. The quality characteristic y was a nonnegative value; the smaller the value was, the more ideal it was, with the optimal value being zero. The S/N ratio for the STB characteristic is defined as follows:

$$S/N_{stb} = -10.\log_{10} (1/n \ \Sigma y_i^2) \quad \text{............................... (1)}$$

The LED desk lamp experiment in this study contained three factors: color temperature, LED array, and diffuser haze. Each factor incorporated three standards. Arranging these factors and standards generated 27 lamp models. The Taguchi method (Park, 1996) was used to identify the most efficient selections. Table I lists the nine selected models in the Taguchi orthogonal array L9.

TABLE I
NINE LIGHT SOURCE MODELS SELECTED FOR THE EXPERIMENT

No.	Color Temperature	LED pitch	Diffuser
1	2700K	1D	No
2	2700K	√2D	50%
3	2700K	2D	90%
4	4000K	1D	50%
5	4000K	√2D	90%
6	4000K	2D	No
7	6500K	1D	90%
8	6500K	√2D	No
9	6500K	2D	50%

In assessments of discomfort in writing and drawing, the participants' subjective cognition of psychological comfort might be affected by the contents of their illustration, causing data deviation. To ensure that the data from the participants focused on their physical fatigue, repetitive patterns were selected for the drawing task. Using only one pattern might also cause visual fatigue in the participants; therefore, to maintain the reliability of the experiment, four distinct patterns were included in the drawing task (Figure 4).

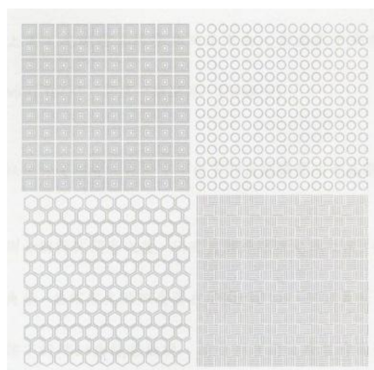

Figure 4 Drawing Task

The study referenced Heuer et al. (1989) in revising the subjective fatigue scale for assessment. The revised scale included eight questions: (a) I felt that my eyes were tired; (b) I felt that my vision was blurred; (c) I felt that my eyelids were heavy; (d) I felt that my eyes were dry; (e) I had a headache; (f) I felt dizzy; (g) I wanted to stop using my brain; (h) the lighting in this experiment is suitable for drawing. All of the questions were answered using a 7-point Likert scale, ranging from strongly disagree (1) to strongly agree (7). The first seven questions addressed negative visual sensations, the responses to which were used for the data analysis, whereas the eighth question addressed positive sensations, the responses to which were incorporated into the reliability test.

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The pretest was conducted to understand the time point when the participants experienced maximal visual fatigue when writing and drawing under the illumination of the nine desk lamp models in the experiment. According to Stern and Skelly (1984), when the blink rate increases to 133% (4/3), visual fatigue is apparent. There were two pretest participants (one man and one woman). The rectified visual acuity of the participants was .8 or higher according to Snellen's E chart. Both of the participants were 20-30 years old, not color-blind or color-weak observers, and experienced in design illustration. The test duration was determined according to the experiment conducted by Bentivoglio et al. (1997) on visual fatigue in reading, in which each participant read for 50 minutes under each lamp model and rested for 10 minutes before switching to the next model, yielding a total test duration of 540 min. The exceedingly long test duration might cause psychological fatigue in participants, affecting the data results. Therefore, the pretest was divided into 3 days and conducted for 180 minutes each day. The results showed that, among the nine models, Model No. 8 caused apparent visual fatigue after 9 minutes of use, whereas the other models caused apparent visual fatigue within 9 minutes of use, thus providing a reference for the subsequent experiment.

D. Experiment Procedures

Nine lamp models were used in this experiment. On the basis of the pretest results, the participants were asked to draw for 10 minutes and to rest for the following 10 minutes, with the total experiment lasting 180 minutes. Each participant completed the experiment over 2 days. The experiment procedures were conducted as follows:

(1) Turn on the lamp, wait for the light source to stabilize, and begin the experiment.
(2) Explain the experiment procedures to the participant and provide additional information to any questions that the participant might raise. If necessary, ask the participant to tie back their hair, thus preventing their eyes from being covered.
(3) Position the light vertically over the center of the desk. Place the drawing task and the questionnaire in front of the participant.
(4) Place the blink rate recorder in front of the participant and to the left; record the blink rate of the participant from an angle lower than their eyes.
(5) Adjust the lighting angle by using an illuminometer (Tenmars TM-202), ensuring that the brightness measures 700 ± 10 lux. Press the timer and recorder buttons and ask the participant to begin the drawing task.
(6) Remind the participant to fill out the questionnaire every two min.
(7) In 10 minutes, after the participant has completed the questionnaire, request the participant to rest. Prepare the next lamp.

III. RESULTS

To confirm the reliability and validity of the subjective fatigue scale, the Cronbach's α from the Likert scale was used to perform a reliability test. The questionnaire exhibited a Cronbach's α value of .842, higher than the value of .7 that Nunnally et al. (1967) recommended, indicating that the questionnaire was within the acceptable range.

The result of the subjective fatigue scale exhibited the STB characteristic. Therefore, Equation (1) was applied to conduct an S/N ratio analysis. The results represented the preferred standards for each factor (Table II). Figure 5 illustrates the S/N influence of each factor.

TABLE II
S/N RATIO OF THE SUBJECTIVE FATIGUE SCALE

Standard	Color Temperature	LED Pitch	Diffuser Haze
1	-11.97	-11.75	-12.02
2	-11.80	-11.85	-11.72
3	-11.83	-12.00	-11.86

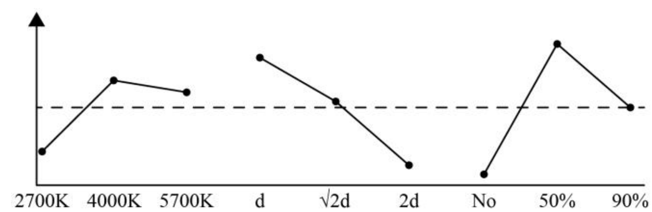

Figure 5 S/N Ratio Of The Subjective Fatigue Assessment

Regarding the results of the objective blink-rate test, the less frequent the participant blinked, the more favorable the result (i.e., exhibiting STB characteristic). Similarly, Equation (1) was applied to conduct the S/N ratio analysis. The results represented the preferred standards of each factor (Table III). Figure 6 illustrates the S/N influence of each factor.

Table III
S/N Ratio Of The Objective Blink Rates

Standard	Color Temperature	LED Pitch	Diffuser Haze
1	-20.80	-20.71	-21.06
2	-20.78	-20.34	-20.79
3	-20.38	-20.92	-20.11

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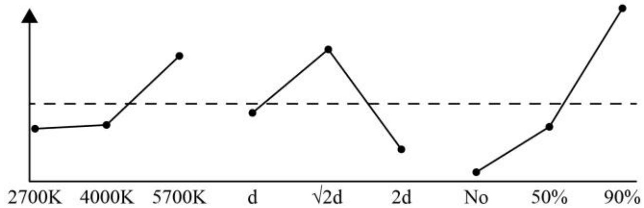

Figure 6 S/N Ratio of the Objective Blink Rates

IV. Discussion And Conclusion

Although LEDs are considered an ideal type of energy-saving lighting, their point illumination characteristic may cause optical multi-shadows and subsequent visual fatigue in users. Most existing LED products on the market are designed for reading. By analyzing the factors of color temperature, LED array, and diffuser haze, this study determined the most suitable LED desk lamp model for writing and drawing. A subjective fatigue scale and an objective blink-rate test were used to understand the similarities and differences between the subjective visual discomfort and the objective visual discomfort of the participants.

Regarding color temperature, both the subjective and objective assessment results revealed that 2700 K (warm colors) was the least suitable lighting for writing and drawing activities. Warm colors caused feelings of relaxation and subsequent eye fatigue in users. The subjective questionnaire revealed that the participants preferred 4000 K (neutral colors). Generally, neutral colors are the most widely used in studios, which are the spaces most prevalently used for writing and drawing. This result is consistent with the subjective assessment of Islam et al. (2015) on office reading. The objective test indicated that the participants blinked the least frequently when using 5700 K (cool colors). This result may be due to cool-colored light sources providing active and cool ambience, thereby improving the work efficiency of users (Boyce and Rea, 1994). Therefore, cool colors were concluded to reduce the blinking frequency of writers and illustrators most effectively. The result of this blink-rate test was similar to the conclusion of Hawes et al. (2012) that higher color temperatures improve work efficiency.

Regarding LED array, both the subjective and objective assessment results implied that 2d (a low-density light source) was the least suitable for writing and drawing. This result was attributed to low-density lighting causing more multi-shadows on the paper when the participants wrote and drew; these multi-shadows changed continually with the moving pens and hands, causing eye fatigue.

The subjective experiment indicated that the participants favored d (a high-density light source). High-density lighting generated the most concentrated light, providing its users with a greater sense of visual comfort when writing and drawing. The objective experiment revealed that the participants blinked the least frequently when using √2d (medium-density lighting), which was similar to the result of Qin et al. (2012). Longer or shorter LED pitches may not provide improved effectiveness. The difference between the LED pitches used in this study and those used in others may be attributed to distinct assessment approaches and usage. In this study, four LED sources were used in each desk lamp model, and the experiment was conducted in a dark room with no other light sources. The neutral-colored luminance was concluded to reduce the blink rates of the participants most effectively when used for writing and reading.

Regarding diffuser haze, both the subjective and objective assessment revealed that the model without a diffuser was the least suitable for writing and drawing. Without a diffuser, the LED point sources of all lamp models generated intense, complex multi-shadows and subsequently caused severe visual fatigue in users. This result is identical to that of Chiang et al. (2015). The subjective fatigue scale indicated that the participants preferred the medium-haze diffusers with 50% haze. The evenness of the lighting generated by this type of diffuser provided the participants with the most natural psychological feeling when writing and drawing. The objective blink-rate test indicated that the participants blinked the least frequently when using the diffusers with the highest hazing (90%), thus generating the most even illumination. This result is consistent with the conclusion of Tsuei et al. (2008), in which the users' eyes were protected more effectively by generating LED light rendered more even by diffusers. Consequently, this type of light was concluded to reduce the blinking frequency of the participants effectively.

On the basis of this study, recommendations were provided to the manufacturers of LED desk lamps produced for writing and drawing. First, as indicated by the subjective fatigue scale and the objective blink-rate test, warm colors and low-density arrays should not be used in LED desk lamp designs, whereas diffusers must be employed. Generally, different production models are designed in the development process. It is recommended that products designed for functional purposes use the optimal factors indicated by the objective test; in other words, cool colors, medium-density pitches, and high-haze diffusers should be used as the design parameters.

It is advised that products designed to satisfy the perceptions of users incorporate the optimal factors indicated by the subjective questionnaire; specifically, neutral colors, high-density arrays, and medium-haze diffusers should be used as the design parameters. On the basis of this experiment, those who design LED desk lamps for writing and drawing should apply cool or neutral colors, medium- or high-density LED array, and medium- or high-haze diffusers, depending on the product's characteristics. Finally, according to this study, LED desk lamps designed for writing and drawing should provide their users with optimal visual comfort, thus creating lamps that are green, energy saving, and visually comforting to the users.

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