Original Article

Relationship between Different Levels of Luminance and Color Temperature of LED Lamps on Human Error and Work Speed in Laboratory Conditions

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Abstract

Aim: The use of appropriate lighting systems can have a significant impact on improving cognitive performance parameters and reducing workplace accidents. The aim of this study was to examine the relationship between different levels of luminance and color temperature of LED lamps on human error and the work speed of individuals in laboratory conditions. **Materials and Methods:** This empirical study was conducted on 12 men and women volunteers. Two LED lamps with two color temperatures of 3000°K and 6000°K were set at angles of 15°, 30°, and 45° and with the same light intensity of 300 lux. Accuracy and work speed parameters were recorded at different time intervals using a target accuracy test. Statistical analysis was performed using SPSS version 26. **Results:** The mean ± standard deviation age of the participants in this study was 20.9 ± 1.2 years, and 50% (6 individuals) were male. The results showed that human error among people in three different angles of luminance for color temperatures of 6000°K and 3000°K was significant ($P < 0.01$), and in terms of the work speed, this difference was not significant ($P > 0.05$). The comparison of error counts and work speed between two color temperatures of 3000°K and 6000°K at all three angles of luminance independently showed a significant difference only in error counts ($P < 0.001$). **Conclusion:** The results demonstrated that the angle of luminance and color temperature have an impact on human error, with individuals exhibiting fewer errors at higher color temperatures. The findings of this research can be utilized in industries that involve high cognitive performance-sensitive occupations.

Keywords: Color temperature, human error, luminance, work speed

Introduction

The use of suitable lighting systems in the workplace can have a significant impact on reducing sleepiness, increasing alertness, improving cognitive performance parameters, and reducing workplace accidents.[1] Employee satisfaction with the physical conditions of the work environment is one of the factors that influence their behavior. Satisfaction with these conditions leads to improved job satisfaction, organizational well-being, and productivity. Good physical conditions in the work environment are closely related to parameters like lighting.[2] Studies have shown that lighting is a significant factor affecting human errors,[3] and inadequate lighting can contribute to industrial accidents.[4]

Sufficient lighting is needed to create a good vision, and reducing or increasing lighting can be effective in causing eye fatigue, headache, visual impairment, glare, mental fatigue, psychological effects as well as nonvisual biological effects.[5,6] Improper and dazzling light, as one of the annoying factors of lighting systems, causes eye and mental fatigue and limits people's field of vision.[7] The presence of some physiological and psychological symptoms such as headache or stress is due to the lack of proper design of lighting systems and dazzling light.[8] Lighting can also affect human performance. Appropriate lighting mainly improves working conditions and increases work efficiency, and can also be effective in creating

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comfort and a satisfactory mental state.[9] The results of some studies show that improving lighting due to faster speed, reducing errors, and reducing accidents and absenteeism can be effective in increasing productivity.[10] Furthermore, designing an optimal lighting system is effective in preventing traffic accidents. One of the main reasons for road accidents in tunnels is the lack of optimal lighting system design.[11]

Luminance level and color temperature are among the important parameters of lighting. It has been reported in a study that color temperature affects some physiological parameters.[12]

Color temperature is defined as a characteristic of the temperature of a light source, which increases the temperature of a black body and emits light at a specific threshold.[13] Color temperature is categorized into cool and warm color temperatures. For example, a color temperature of 5000°K is considered a cool color temperature and is close to blue, while a color temperature of 3000°K is considered a warm color temperature and tends to be reddish.[14]

The effects of lighting are dependent on parameters such as color temperature, light intensity, and exposure duration.[1] Studies on the effects of lighting on humans are complex, and in addition to its effects on vision, it also affects the circadian rhythm and mood. Positive effects of lighting on individuals' performance and a decrease in accident rates have been reported in studies.[15,16] Lighting conditions have been identified as one of the factors affecting visual and nonvisual (physiological and psychological) performance and the circadian rhythm.[17] The study by Luo *et al*. showed that color temperature control is evident in visual and alertness tasks, and color temperature significantly affects individuals' cognitive performance depending on the task type.[18]

Furthermore, luminance is a very important factor in visual performance. Luminance is divided into three categories: limiting luminance, incapacitating luminance, and suitable luminance. Incapacitating luminance leads to a decline in individuals' performance. A study conducted by Huang and Menozzi showed that irritating luminance caused a reduction in visual performance.[19] Illumination has a significant effect on all aspects of human life, as well as physiological and psychological health. Glare causes distraction and reduces individuals' performance.[20]

As mentioned, exposure to inappropriate light can cause disturbances in the visual system and mental performance of people. In past studies, the effect of various lighting factors such as lighting intensity and color temperature on human error and work speed has been investigated, and in most studies, lighting sources with different lighting intensities have been considered for the test environment. However, in this study, instead of using sources with different lighting intensities, by placing the lamp at different angles to the line of sight of people, the effect of luminance and also the simultaneous effect of the color temperature of the light source on cognitive performance parameters have been investigated. Furthermore, considering the need for angled installation of lamps in work areas such as some assembly rooms, study rooms, projectors in industries, halls, and conference rooms, dental units, surgical rooms, and the lack of investigation into the effect of luminance at different angles on cognitive performance parameters and the importance of the impact of lighting in reducing accidents and improving individuals' performance, this study was conducted to examine the relationship between different levels of luminance and the color temperature of LED lamps on the human error and work speed of individuals under laboratory conditions.

Materials and Methods

Study design and participant selection

This study was conducted in the summer of 2021 among 12 students (six males and six females) at the Lighting Laboratory of Isfahan University of Medical Sciences. After reviewing previous studies, the sample size of 12 participants was determined. The participants were selected using simple random sampling from students of a single academic field, with a passing grade on the exam and from a specific educational level. The inclusion criteria for the study included having healthy vision, no history of undergoing the specific experiment, no consumption of any medication before the experiment (excluding blood sugar-lowering drugs, cardiac medications, antidepressants, sedatives, antihistamines, and Parkinson's medications), having sufficient sleep on the night before the experiment, and signing the informed consent form to participate in the study. The exclusion criteria included participants withdrawing from the experiment and participants incorrectly experimenting. Before the start of the experiment, participants' visual health was assessed using the Snellen chart, and other entry criteria were assessed by questioning the individuals under investigation.

Measurement tools and experimental procedure

The experiment was conducted at the Lighting Laboratory of the School of Health, Isfahan University of Medical Sciences. The laboratory was free from any windows to eliminate any interfering light and sunlight intervention. For the experiment, two 20-watt LED lamps with two color temperatures of 3000°K and 6000°K were used at three angles: 15°, 30°, and 45°.

In this study, human error and work speed in the color temperature of sunlight and moonlight and the effect of placement of lighting sources at different angles about people's line of sight are investigated. For this reason, an LED lamp close to sunlight with a color temperature of 3000°K and an LED lamp close to moonlight with a color temperature of 6000°K were used.

Since the correct design of the placement of lighting sources is effective in reducing glare and improving visual comfort, and so far in previous studies, the effect of luminance on the line of sight of people has not been investigated; for this reason, the level of luminance at an angle of 15°, 30°, and 45° compared to the line of sight of people was checked.

To assess the work speed and the number of errors, a precision targeting device was utilized. To ensure the creation of standardized and desired conditions in the experimental chamber, the light intensity was fixed at 300 lux for all measurement conditions using a lux meter, the color temperature of the light sources was measured using a Kelvin meter (TES model), and the luminance intensity was measured using a luminance meter (TES model) in units of nit (cd/m^2). Furthermore, to eliminate the disturbing effect of heat, thermal comfort conditions were created in the laboratory test chamber.

After explaining the test conditions and reviewing the entry criteria, the informed consent form was provided to the participants. Once the consent form was signed, the test commenced. The cognitive performance test using the accuracy targeting device was conducted at four time points: baseline (start of the test), 5, 10, and 15 min after the start of the test, at each angle, and for both color temperatures, repeated by the participant.

The recorded data for work speed and human error were summed for each of the four time points, and the mean values were calculated for each of the three angles and both color temperatures. Subsequently, statistical analyses were conducted on the data.

In a study by Mork *et al*., which examined the relationship between luminance and cognitive performance, participants were exposed to the light of the lamp and luminance being tested before performing the cognitive test for 10 min.[21] In the present study, as a pilot, a 5-min interval between exposure to light, luminance angles, and performing the precision targeting test was initially considered. Based on the obtained responses and suitable results, this time interval was determined for the study. To prevent participant fatigue and its adverse effects on the results among different luminance angles, a 5-min break was included.

The Target Accuracy Test is part of the Job Skills Assessment Battery, which examines various aspects of an individual's coordination between their eyes and hands, task speed, accuracy, perceptual and motor skills, coordination between both hands, and more. The Target Accuracy Test consists of a metallic pen and a device with 10 progressively smaller holes. The participants positioned themselves facing the device and inserted the metallic pen into each hole, without touching the walls of the device, to a depth of 5–10 mm before retracting it. The test begins with the largest hole and concludes with the smallest. Each time, the pen touches a wall, it is considered an error, and both the number of errors and the test duration are recorded using a chronometer to measure speed. Completing the test in a shorter time indicates a higher speed for the participant. The validity of this test has been confirmed by various articles.[22,23]

Statistical analysis

For the descriptive analysis of the quantitative data, the mean and standard deviation were used. After assessing the normality distribution of the data using the Shapiro–Wilk test, parametric tests, including paired *t*-test and repeated measures ANOVA, were employed to examine the relationships between the parameters. The data analysis was performed using SPSS software version 26 (IBM Corp, Armonk, New York), and the accepted level of significance in this study was set at $P < 0.05$.

Results

The mean ± standard deviation age of the participants in the current study was 20.9 ± 1.2 years, and 50% (6 individuals) of them were male. The mean luminance at three angles (15°, 30°, and 45°) at a color temperature of 3000°K was 84.33, 49, and 25 cd/m², respectively, while at a color temperature of 6000°K, it was 69, 40.33, and 20.33 cd/m². The results of comparing the mean human error among the three angles of luminance (15°, 30°, and 45°) at a color temperature of 6000°K using repeated measures ANOVA in the target accuracy device showed a significant difference in the human error among the three angles of luminance ($P < 0.001$). In addition, there was a significant difference in the mean human error among the three angles of luminance at a color temperature of 3000°K ($P < 0.001$). However, there was no significant difference in the work speed among the three angles of luminance (15°, 30°, and 45°) at both color temperatures of 6000°K and 3000°K in the target accuracy device ($P > 0.05$). Further details are provided in Table 1.

The results of comparing the mean human error between the two color temperatures of 3000°K and 6000°K in each of the three luminance angles, using an independent paired *t*-test, showed a significant difference in the human error between the two color temperatures ($P < 0.001$). However, comparing the mean work speed between the two color temperatures of 3000°K and 6000°K in each of the three luminance angles, independently, showed no significant difference in the work speed of the participants between the two color temperatures (3000°K and 6000°K) in each of the three angles (15, 30, 45) ($P > 0.05$). Further details can be found in Table 2 and Figure 1.

Discussion

The aim of this study was to examine the relationship between different levels of luminance and color temperature of LED

Table 1: Comparing the average human error and the work speed in three luminance angles (15, 30, and 45) (*n*=12)

Parameter	Angle (°), mean±SD			*P*
	15	30	45	
Color temperature 6000°K				
Number of errors	6.2±0.7	5.5±0.9	2.9±0.2	<0.001
Work speed	7.9±0.4	7.9±0.3	8.2±0.6	0.194
Color temperature 3000°K				
Number of errors	8±1.1	6.6±1.2	4.9±0.4	<0.001
Work speed	7.8±0.7	8±0.5	8.1±0.6	0.604

n: Number of people, SD: Standard deviation

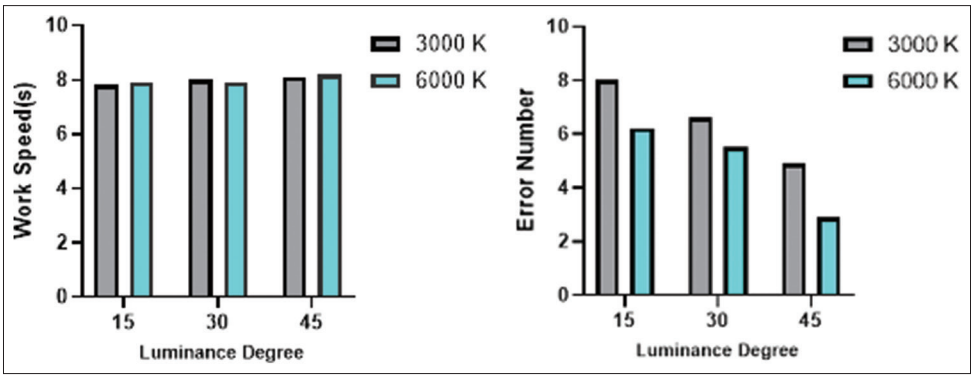

Figure 1: Comparison of the number of errors and the work speed in the luminance levels measured between two color temperatures of 3000°K and 6000°K

Table 2: Comparing the average human error and work speed between the color temperature of 6000°K and 3000°K

Parameter	Angle (°)					
	15		30		45	
	MD	*P*	MD	*P*	MD	*P*
Number of errors	−1.7	<0.001	−1.1	0.015	−1.9	<0.001
Work speed	0.1	0.666	−0.6	0.722	0.1	0.723

MD: Mean difference

lamps on the human error and work speed of individuals under laboratory conditions. The results of the current study showed a significant correlation between human error at different luminance angles in both color temperatures of 3000°K and 6000°K. This difference was related to the luminance angle of 45° at 6000°K color temperature and the luminance angle of 30° at 3000°K color temperature. In other words, the level of luminance affected human errors, and the luminance angle varied in the two different color temperatures. However, in both color temperatures, the human errors were higher at the luminance angle of 15° compared to other angles, indicating that individuals make more errors at this luminance angle. Moreover, at higher angles, including 30° and 45°, they have fewer errors.

However, the results of the current study regarding work speed showed no significant difference in work speed among individuals at different luminance angles in both color temperatures of 6000°K and 3000°K. In other words, the work speed of individuals is not influenced by different luminance angles.

Part of the results of this study were consistent with the findings of Huang and Menozzi, which demonstrated that bothersome glare adversely affects visual performance and is a significant factor in visual tasks, leading to a decline in visual performance.[19] In addition, it aligns with the findings of Rodriguez *et al*., who showed that different levels of glare influence cognitive performance parameters, including reaction time.[24] Theeuwes *et al*. also demonstrated in their study that bothersome glare significantly affects individuals' driving performance and disrupts it.[25] One of the differences in the present study compared to other studies conducted in this area was the examination of parameters and cognitive performance in two types of irritating and nonirritating luminance. The difference in performance type and cognitive performance parameters was evident. Performing tasks in two types of annoying and non-annoying luminance and the difference in the type of performance and cognitive performance parameters was the difference between the present study and other studies conducted in this regard, and the results of the study showed that different levels of luminance, including annoying luminance, caused It reduces some parameters of people's cognitive performance. Furthermore, according to the current study, significant differences were observed in human error between the two color temperatures of 6000°K and 3000°K at all measured angles of luminance. Individuals had fewer errors at a color temperature of 6000°K compared to 3000°K, indicating that color temperature affects human error. In other words, higher color temperature results in fewer errors in individuals. However, the results regarding the work speed showed no significant difference between the work speed of individuals at the 3000°K and 6000°K color temperatures. In other words, the work speed is not affected by color temperature. These findings are consistent with the research conducted by Beheshti *et al*., which demonstrated that increasing color temperature leads to a decrease in human error, and at 6500°K color temperature, the human error is lower compared to lower color temperatures.[13] In addition, it aligns with the findings of Luo *et al*., who showed that alertness, thermal comfort, and cognitive performance improve at 5700°K color temperature, and increasing color temperature is a significant factor in enhancing the mentioned parameters.[26] The research by Lee and Kim which examined working memory at color temperatures of 3000, 5000, and 7000, and different illumination intensities, also revealed that individuals have better working memory at a color temperature of 5000 and an illumination intensity of 1000 lux.[16] Based on the results of the present study and previous research, it can be concluded that color temperature has an impact on some cognitive performance parameters, including human error, and individuals perform better at higher color temperatures, especially temperatures close to sunlight."

Considering the need for angled installation of lamps in work areas such as some assembly rooms, study rooms, projectors in industries, halls, conference rooms, dental units, and surgical rooms, this study aimed to investigate the relationship between different levels of luminance and color temperature of LED lamps on the human error and work speed in laboratory conditions was carried out. Among the limitations of this study, we can refer to the small sample size, not considering all variables that can affect individuals' cognitive performance, the small number of LED lamps examined, not paying attention to the difference in people's skills, and not using the standard tests. Furthermore, the results of this study relate to only two LED lamps, and the results may differ for other lamps. It is recommended to have a larger sample size in future studies and to examine the effect of gender on these parameters. In addition, considering the use of the results in work environments, it is suggested that more studies be done in other age ranges and among workers in different jobs to reach a correct understanding of this issue.

Conclusion

The study's findings indicate that the angle of luminance affected human error, with fewer errors occurring at angles of luminance >45° and 30° compared to an angle of 15°. Similarly, color temperature also influences human error, as individuals working in higher and closer-to-sunlight color temperatures have fewer errors compared to lower color temperatures. However, the work speed is not affected by color temperature and luminance. These study results can be applied to professions that require high cognitive performance, like control room operators in industries, to use suitable lamps with appropriate color temperature and luminance to increase efficiency and reduce errors.

Ethics code

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Author contributions

Subject selection and study design: Habibi E and Dehghan H; article writing and data collection: KhajehVarnamkhasti Z; and article writing and data analysis: Dabaghi E.

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Conflicts of interest

There are no conflicts of interest.

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