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Effect of Color Temperature and Illuminance on Psychology, Physiology, and Productivity: An Experimental Study

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Abstract: In this study, we investigated the impact of the lighting environment on psychological perception, physiology, and productivity and then designed lighting control strategies based on the experimental results. The research was conducted in a smart lighting laboratory, and 67 subjects were tested in different illuminances and correlated color temperatures (CCTs). During the experiment, the physiological data of subjects were continuously recorded, while the psychology and productivity results were evaluated by questionnaires and working tests, respectively. The experimental results found that both illuminance and CCT could significantly influence the feeling of comfort and relaxation of the subjects. Warm CCT and higher illuminance (3000 K–590 lux) made subjects feel more comfortable. Productivity reached its maximum value with illuminance above 500 lux and equivalent melanopic lux (EML) higher than 150. The brain-wave and heart-rate changes did not have a close relationship with either illuminance or CCT, but the heart rate slightly increased in the adjustable lighting mode. Regardless of the initial value setting, the subjects preferred intermediate CCT (4200 K) and bright illumination (500 lux) after self-adjustment. Finally, we proposed three comprehensive lighting control strategies based on psychology, productivity, circadian rhythm, and energy-saving.

Keywords: lighting environment; experimental designs; productivity; satisfaction; lighting control

Citation: Chen, R.; Tsai, M.-C.; Tsay, Y.-S. Effect of Color Temperature and Illuminance on Psychology, Physiology, and Productivity: An Experimental Study. *Energies* **2022**, *15*, 4477. https://doi.org/10.3390/en15124477

Academic Editor: Tullio De Rubeis

Received: 26 May 2022
Accepted: 18 June 2022
Published: 20 June 2022

1. Introduction

1.1. Background and Literature Review

These days, people spend almost 90% of their time in indoor environments. Indoor environment quality (IEQ) has begun to play a more important role in people's daily lives [1,2]. The impact on occupants of various environmental factors of buildings has been actively studied [3,4]. Among them, lighting conditions have been shown to have a significant influence on all aspects of human life and health [5]. They can affect both the physiological and psychological health of people, and dynamic lighting changes have a positive impact on several aspects of human well-being, such as spatial perception, emotional state, and biological rhythm [6–8]. Although the lighting environment is influenced by numerous complicated parameters, the two main characteristics are CCT and illuminance, which have been researched in many previous studies [9–11]. With the development of lighting research, the academic topic of building environment has not only focused on the impact of daylight and artificial lighting on building performance but also expanded to the effect of lighting on comfort, health, and work productivity [12–14].

Furthermore, no uniform quantitative standard is available for CCT and illumination values in office buildings. For example, in Taiwan, the lighting standard CNS 12112 stipulates that the average illumination of the workspace in an office for writing, typing, reading, and data processing should be at least 500 lux, which is similar to the international standard CIE S 008/E-2001 [15,16]. However, in Japan, the illuminance is required to be in the range of 500 to 750 lux in ordinary offices, while the British Institute of Lighting Engineering recommends 750 lux for designing and typing in offices. The WELL building standard is a health building-design standard for different categories issued by the international WELL building institute in 2014 [17]. WELL also has many regulations for lighting, such as visual lighting design, circadian lighting design, low-glare design, etc. In WELL, for all workstations, electric lights need to maintain illuminance on the vertical plane facing forward (to simulate the view of the occupant) of 150 equivalent melanopic lux (EML) or greater. According to the International Commission on Illumination (CIE), the illuminance produced by light-emitting diode (LED) lamps needs to consider the spectral mismatch correction factor (SMCF) [18,19]. It can correct the measurement error of the luxmeter because the spectral sensitivity of the luxmeter does not completely match the required one and may vary with different instruments [20]. Meanwhile, when evaluating LED lamps, not only CCT but also chromaticity point and binning should be considered [21].

Numerous studies have shown that a light environment can directly influence work efficiency through visual effects while indirectly affecting people's attention, enthusiasm, and arousal level. Sun et al. [22] found that the illumination on the work plane had the most significant impact on visual comfort, and the CCT of the light ranks second. Ishii et al. [23] found that the task performance of the subjects under high CCT (6200 K) was better than that of normal CCT (5000 K). Figueiro et al. [24] suggested that appropriate light application could promote circadian rhythm and improve alertness. Chraibi et al. proposed that the sensor-triggered lighting control strategy could solve the problem of energy-saving use of electric lighting without affecting the user experience. Huang et al. [25] found that subjects preferred whiter illumination when the CCT value was between 2500 K and 5500 K. Furthermore, Dangol et al. [26] found that in an office, workers preferred 500 lux rather than 300 lux illuminance for working and a CCT of 4000 K rather than 6500 K under the lighting condition of 500 lux.

Jihyun et al. [27] proposed that the illuminance level of 406 lux for the work surface reaches the best satisfaction level in contemporary office environments. Hviid et al. [28] changed the lighting situation from 2900 K–450 lux to 4900 K–750 lux and found that the processing speed, concentration level, and mathematical skills of pupils improved significantly. Shamsul et al. [29] indicated that their subjects preferred the CCT of 4000 K, but the best subjective attention level, including the correct rate of typing and execution ability, was at a CCT of 6500 K. Houser et al. [30] pointed out that when designing light strategies, circadian rhythm, neuroendocrine, and neurobehavioral responses were as important to human health as visual responses. Zhai et al. [31] indicated that illumination had a greater impact on visual perception than CCT. Islam et al. [32] proposed that staff tended to have task illuminance of 500 lux to 300 lux and CCT of 4000 K to 6500 K. Veitch et al. [33] pointed out that higher-quality office lighting could make subjects have more pleasant mood and happiness. Ye et al. [34] suggested that the subjects showed better performance and the higher alertness under the illumination of higher CCT range. Park et al. [35] indicated that the occupants prefer a different CCT according to the function of the space, as well as that a changeable CCT was better than a fixed CCT for subjects.

The relationship between physiological changes and the light environment has also been studied by many researchers. The electroencephalograph (EEG) and electrocardiogram (ECG) have been widely applied in subjective sensory and cognitive tasks, which can be used as an objective index to support traditional subjective methods and productivity evaluation [36,37]. Baek et al. [38] found that blue light (short wavelength) significantly reduced EEG alpha activity but increased work productivity after lunch. Michal et al. [39] confirmed that short-wavelength light could enhance cognitive efficiency in task-specific scenarios. Eroglu et al. [40] proposed that the types and luminance of visual stimuli can be revealed by changing the activity power of the brain. Yosuke et al. [41] suggested that the power in the alpha frequency range of brain waves decreased significantly after half an hour of exposure to both short- and long-wavelength light. Lasauskaite et al. [42] increased CCT from 2800 K to 6500 K and found that the average heart rate decreased by almost 1.5 beats per minute (bpm). Omidvar et al. [43] compared different CCT conditions and indicated that the activation of non-visual photoreceptors could lead to melatonin inhibition, thus increasing heart rate and warmth. Other recent research is summarized in Table 1, including experimental details and research points.

Table 1. Representative experiments in lighting research literature.

Ref.	CCT (K) Illuminance (lux)	Experiment Method	Physiological & Psychological Measurement	Productivity Measurement	Conclusions
[44]	1 CCT (5000) 3 illuminances (200, 500, 1000)	Fixed lighting/3 groups	1. EEG 2. heart rate 3. skin temperature 4. engagement level	1. number addition 2. visual search 3. digit recall	- The influence of lighting level on work engagement varies across different individuals.
[45]	3 CCTs (3000, 4500, 6000) 1 illuminance (300)	Fixed lighting/3 groups	1. ECG 2. thermal sensation and comfort 3. light satisfaction and comfort	1. short-term memory test	- CCT can change thermal sensation of environment when the temperature difference is less than 2 °C.
[46]	3 CCTs (3000, 4000, 6000) 5 illuminances (75, 100, 200, 300, 500)	Fixed lighting/15 groups	1. ECG 2. luminance 3. color authenticity 4. fatigue 5. relaxation	1. reading	- CCT affects reading efficiency significantly. - Illuminance affects the response of the vision.
[47]	3 CCTs (2800, 5000, 6700) 2 illuminances (150, 300)	Fixed lighting/6 groups	1. luminance 2. security sense 3. pressure 4. positive feelings 5. fatigue	1. reading	- Higher CCT relates to higher spatial luminance. - Security sense was influenced by CCT rather than illumination.
[48]	5 illuminances (300, 500, self-adjust)	Fixed and adjustable lighting/5 groups	1. visual perception 2. self-rated productivity 3. satisfaction level	-	- Memory mode is better than forgetting mode. - Regardless of conflicts, controllable is better than uncontrollable.
[49]	2 CCTs (3000, 6500) 2 illuminances (100, 1000)	Fixed lighting/4 groups	1. KSS 2. Psycho-motor vigilance test	1. Go/No-go test 2. Flanker test 3. working memory task	- Fatigue was reduced at 6500 K and 1000 lx. - Reaction was highly increased in 1000 lux compared to 100 lux.
[50]	9 CCTs (2500–6500) 1 illuminance (200)	Fixed lighting/9 groups	1. six different jeans 2. color preference 3. color discrimination	-	- CCT affects color recognition of subjects.
[51]	2 CCTs (2700, 5800) 2 illuminances (5, 1200)	Fixed lighting/4 groups	1. core body temperature 2. skin temperatures 3. energy expenditure 4. thermal perception 5. visual comfort	-	- Changes in visual comfort and thermal comfort were related. - Lighting can partially compensate for thermal discomfort.
[52]	CCT (4000) illuminances (variable)	Adjustable lighting/9 groups	1. visual perception 2. comfort level	1. typing 2. reading 3. look at clock and tree	- The difference of light environment is small and better.
[53]	2 CCTs (2700, 6000)	Fixed lighting/4 groups	1. Electro-dermal activity (EDA) 2. ECG 3. visual experience 4. comfort level	1. image response 2. number operation 3. find fault 4. image change	- CCT is the most important factor affecting the mood, but no obvious effect on health, psychology, productivity.
[54]	2 CCTs (2700, 6500)	Fixed lighting(from 20 to 24 °C)/2 groups	1. thermal perception 2. personal acceptability 3. affective assessment	-	- Participants feel colder at high CCT. - Participants have high comfort level at lower CCT.
[55]	4 illuminances (self-adjust)	Adjustable lighting/4 groups	1. visual perception 2. comfort level	1. reading 2. identify difference	- The default value is better than the preferred value.
[56]	4 CCTs (2700, 4300, 6500), 1 illuminance (500)	Fixed lighting/3 groups	1. visual perception 2. comfort level	1. Chu attention test	- CCT affects concentration, especially 4300 k.

1.2. Aims and Originality

However, based on the literature review, few studies have comprehensively considered the lighting condition with regard to physiology, psychology, work efficiency, and energy consumption. Furthermore, almost no relevant lighting experiments have been conducted in Taiwan [57]. Therefore, this paper aims to research the effects of CCT and illuminance on human psychology, physiology, and work productivity and to propose a personalized lighting control schedule for offices. Five kinds of light situations—three fixed lighting and two adjustable lighting modes—were applied to 67 subjects in this experiment. The experiment was conducted in a lighting laboratory without daylight. Users' results were collected to analyze the differences in personal preferences, physiological changes, and productivity for these lighting conditions. Then, we compared the relationship and correlation of each variable factor and finally proposed some recommended lighting control schedules based on the experimental analysis. The originality of this study lies in three aspects:

- It was the first lighting experiment in Taiwan to explore the local effects of CCT and illuminance on human psychology, physiology, work productivity, and energy-saving;
- This study developed the experimental lighting strategies based on the level of 150 EML in the WELL standard;
- Three new lighting control schedules were proposed for the public based on the experimental results.

The rest of this paper includes the following sections: Section 2 introduces the experimental procedures and the evaluation methods of the experiment. Section 3 shows the results and discussion of experimental results and the lighting schedules. The work is summarized in Section 4.

2. Methodology

2.1. Overview

In this study, we carried out a lighting control experiment that included experiment content design, human ethics review, laboratory equipment preparation, data collection, result analysis, and more. The experiment addressed changes in subjective psychological feelings and objective work productivity of the subjects in different lighting environments, concluded the preference range of human eyes in light color and luminance, and explored the relationship between lighting control and satisfaction with various light environments.

The purpose of this study was to investigate the effects of different lighting environment factors on human psychology, physiology, and work productivity. The experiment process and all the other details are shown in Figure 1. The lighting situation of this experiment can be divided into two categories—fixed lighting and adjustable lighting—in which the lighting in the latter can be adjusted to the subject's preferred lighting environment. The experiment included six kinds of fixed lighting with different CCT and horizontal illumination, as well as EML. EML is a value obtained by quantifying the influence of light on the circadian cycle of the human body. According to the type of light source, EML is calculated by multiplying photopic illuminance by the melanin ratio [58]. This study refers to the circadian lighting design in WELL standard, and the EML calculation formula is as follows:

$$\mathrm{EML} = \mathrm{L} \times \mathrm{R} \tag{1}$$

where the L is the visual illuminance (lux); R is the melanopic ratio.

$$\mathrm{R} = \frac{\mathrm{M}}{\mathrm{V}} \times 1.218 \tag{2}$$

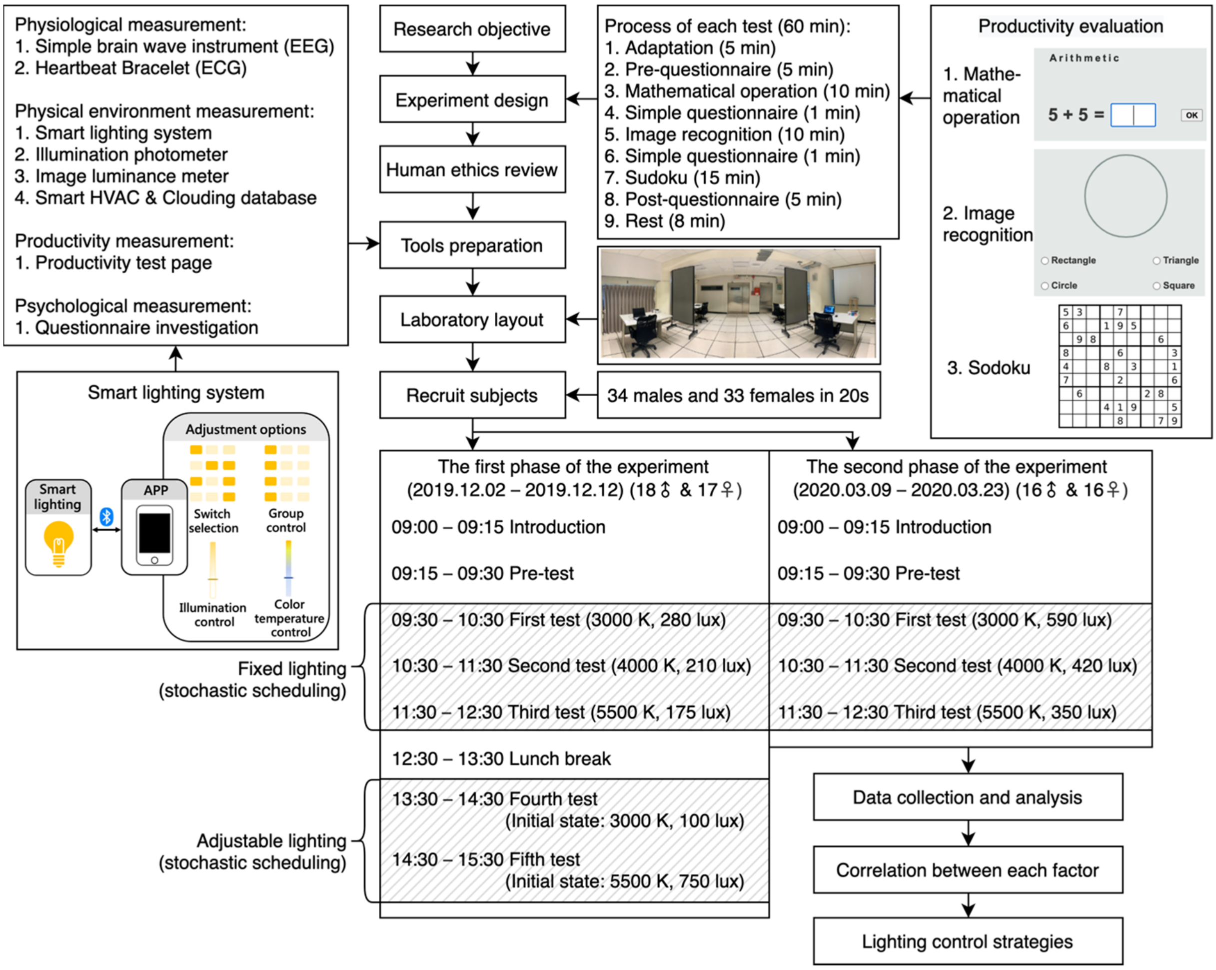

Figure 1. The complete research processes and details of the experiment.

As shown in Equation (2), to calculate the R value of light, start by obtaining the light output of the lamp at each 5 nm increment. Then, multiply the output by the melanopic and visual curves to get the melanopic and visual responses. Finally, divide the total melanopic response M by the total visual response V and multiply the quotient by 1.218 [17]. In this study, the R values of CCT 3000 K, 4000 K, and 5500 K are 0.43, 0.59, and 0.85, respectively.

The difference between the two adjustable situations was the initial value of CCT and illuminance. One initial state was high cold CCT and high illumination (5500 K–750 lux); the other was low warm CCT and low illumination (3000 K–100 lux). Finally, in the data analysis, the statistical software SPSS was used for simple regression analysis and independent sample *T*-test. The significant (*p*) results of *T*-test are highlighted in a table: $p < 0.05$ is marked with *; $p < 0.01$ with **; $p < 0.001$ with ***.

2.2. Field Study

The smart air conditioning and lighting laboratory is located in the National Cheng Kung University (NCKU), Taiwan. The panorama and plan of the laboratory are shown in Figure 2. The smart lighting system is applied in the laboratory, which consists of adjustable lamps and a mobile app. There is an intelligent lamp above each seat, and the size of each intelligent lamp is 601 × 601 × 13 mm. When the lamp is turned on, it automatically connects to the app via Bluetooth. Then, the luminance and CCT of each lamp can be adjusted by subjects in the app. The preset CCT is 4000 K, and the luminance is 500 lux. The preset state was restored each time the light was turned off and then on again. In this study, a spectrometer was used to measure the horizontal illumination, CCT, and EML at the desktop. In the experiment, the minimum and the maximum values of CCT were

3000 K and 5500 K, respectively. The illuminance level on the desktop was from 170 lux to 590 lux, while the EML value was between 120 and 300.

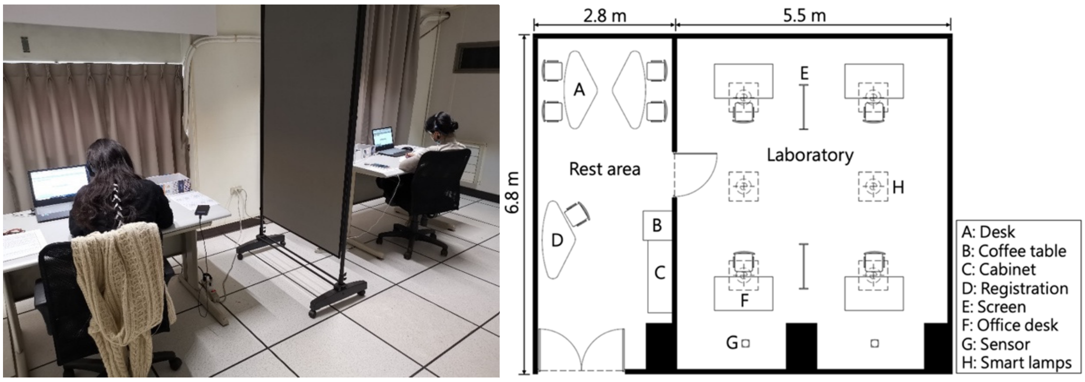

Figure 2. The picture and plan of the laboratory.

This research project was approved by the NCKU Human Research Ethics Committee (Approval number: No. NCKU HREC-E-108-359-2). The contents of the review included the experiment plan, the recruitment information, the questionnaire, and the informed consent form for the experiment [59]. The experimental process was in line with public morality and research ethics in Taiwan. The experimental personnel underwent prior research ethics education and training. In the process of the experiment, the subjects were informed of all their rights and obligations and fully respected each experimental object.

2.3. Experimental Procedures

The sample size of the experiment was determined to be greater than 30 because the normal distribution of statistical analysis based on the central limit theorem was considered [60,61]. The subjects were NCKU students in their 20s, including 34 males and 33 females. They did not have any major organ diseases or physiological abnormalities, and their corrected visual acuity was between 1.0 and 1.2. The subjects were asked to get enough sleep and could not take any therapeutic drugs the day before the experiment. In the laboratory, they were asked to wear trousers and short-sleeved tops (0.7 clo). The experiment was divided into two phases. The first phase was from 2 December 2019 to 12 December 2019, while the second phase was from 9 March 2020 to 23 March 2020. In the first phase, the experiment started at 09:00 and continued after lunch for two hours until 15:30. In the second phase, because there was no adjustable lighting test, the experiment started at 09:00 and ended at 12:30.

The WELL standards indicate that all working areas should be above 150 EML. In the first phase, EML was lower than 150 and can be subdivided into fixed and adjustable lighting modes. Thus, the illumination values in the first phase of the experiment were relatively low. The fixed lighting scenarios were 3000 K–280 lux–120 EML, 4000 K–210 lux–120 EML, and 5500 K–175 lux–145 EML, respectively. On the other hand, EML was higher than 150 in the second phase, and only the fixed lighting mode was tested, including 3000 K–590 lux–250 EML, 4000 K–420 lux–250 EML, and 5500 K–350 lux–300 EML. In the adjustable lighting mode, the subjects can adjust illuminance and CCT according to their preference. On the contrary, they could not control lamps in the fixed lighting mode. EML is an index for measuring the biological effect of light on the human body, which indicates the relative circadian rhythm effect of different light sources [62].

The experiment process and all the other details are shown in Figure 2. The first phase had five tests, while the second phase had three tests, which took 5.5 h and 3.5 h, respectively. To avoid the specific results caused by a single lighting environment, the test sequence was randomly arranged in the experiment, and the two genders were equally assigned. For each test, the subjects entered the laboratory to adapt to the light environment for 5 min. Then, they had another 5 min to complete the pretest questionnaire, recording their feeling about the current light environment. The first test was a mathematical operation that took 10 min. After that, participants had 1 min to fill out a simple questionnaire that only included the top five questions in the questionnaire. The second test was image recognition on the computer. At the end of the 10-min image-recognition test, participants again had 1 min to fill out a simple questionnaire. The third test was Sudoku, and participants were given 15 min to complete it. After the paper Sudoku test, 5 min were provided for filling out the post questionnaire.

2.4. Subjective Psychological Evaluation

In this study, we used the questionnaire to evaluate the psychological effects of different lighting environments for subjects. The design of the questionnaire adopted the semantic differential technique (SDT) as the principle of evaluation. The adjectives of the questionnaire were defined according to the implementation steps of SDT and relevant literature [5,8,26,52,63,64]. The evaluation contents included work productivity, mental state, light environment luminance, light environment feeling, emotional influence, light CCT, overall comfort, etc. The evaluation scale of all content was divided into seven levels, from −3 to +3, except for the Karolinska sleepiness scale (KSS) [65]. The questionnaire is presented in Appendix A. The original questionnaire was written in traditional Chinese and translated into English with professional vocabulary for readers to read. The description of the seven categories of the psychological evaluation items is shown below:

- Self-evaluative work performance: The assessment of self-evaluative work performance caused by different lighting environments included "suitable or unsuitable" for the current lighting environment, "easy or difficult" for the lighting environment to effectively focus, and "bad or good" for the self-assessment of work performance;
- Mental state: KSS was used to evaluate whether the subjects' lighting environment caused drowsiness to indicate whether they were in a good mental state [65]. KSS is often used as a sleepiness assessment tool in lighting and human response experiments. The scale has nine levels: "1" for extreme wakefulness; "5" for neither sleepy nor wakeful; and "9" for extreme sleepiness;
- Luminance of light environment: For the luminance of the light environment, it has desktop luminance perception "dark or bright", screen luminance perception "dark or bright", glare level "serious or unserious", and overall luminance distribution "even or uneven;"
- Light environment sensation: The light source was divided into luminance and CCT to evaluate the satisfaction and acceptance of subjects, including the evaluation of lighting environment "satisfaction or dissatisfaction", light luminance "satisfaction or dissatisfaction", light CCT "acceptance or unacceptance", and light luminance "acceptance or unacceptance;"
- Emotional impact: The psychological feelings of the subjects in different lighting situations included the influence degree of the current lighting environment on mood "affected or unaffected" and the feeling "relaxed or nervous" and "comfortable or uncomfortable" in the current lighting environment;
- Light CCT: The subjects' perception of light color in different lighting environments was evaluated, and the subjects were asked what light color they thought was "cool or warm;"
- Overall comfort: The comfort of the subjects was evaluated, including the thermal environment and overall environment. The subjects were asked to fill out the comfort level with seven levels to feel "comfortable or uncomfortable".

2.5. Work Productivity Evaluation

In this study, productivity was evaluated by the work performance series (ASL) and the differential attention test (DAKT). The ALS is a simple computing ability test, while the DAKT is a difference attention test to identify different numbers, English letters, and images in a short time [66]. Considering the application trend of modern science and technology, the experiment used notebook computers as a tool to measure work productivity. The metabolic capacity of the subjects was 1.2 met (70 W/m^2) while working and typing in a sitting position. Samples are shown in Figure 2.

In the ASL part, the mathematical operation test mainly measured how the subjects' concentration, accuracy, and speed changed with time. During the test, the subjects had to answer the question of adding and subtracting two numbers as quickly as possible. The number was displayed on the screen. In the DAKT part, the image-recognition test mainly measured how subjects' concentration, accuracy, and speed changed with time. The image-recognition test had seven kinds of images, including circle, triangle, rectangle, pentagon, hexagon, heptagon, and octagon. The subjects had to select the correct name of the image on the screen from four options. After pressing the answer, the next question was immediately generated. The test time for ASL and DAKT was 10 min. The Sudoku test mainly measured the subjects' inductive processing, logical analysis, concentration, spatial position confirmation, and information arrangement. Sudoku is composed of 81 squares arranged in a 9*9 format. In the form, the number of each row and column should be filled in from 1 to 9 and should not be repeated. The Sudoku test was a paper test, and participants were given 15 min to complete it. The number of questions was not limited. As soon as the answer time arrived, the subjects were immediately stopped and could not answer anymore. The total number of answers, the number of correct and wrong answers, and other information were all recorded on the computer.

2.6. Physiological Changes Evaluation

We used EEG and ECG to assess the physiological changes of subjects in the experiment and removed them during the rest period [67]. The data were recorded continuously during the experiment. As brain waves affect changes in concentration, to find out the biological effects of different light environments on the subjects, a simple brain wave instrument was used to measure the subjects' concentration or relaxation state to determine the degree of influence of the changes of the external light environment. When the human brain frequency is at α waves (8–12 Hz), the person's consciousness is clear, and the body is relaxed, so α waves are the best brain wave state for people to learn and think. Meanwhile, when the brain is awake, the frequency is primarily in the β wave (13–25 Hz) state. As β waves increase, the body gradually becomes tenser [68]. This study focused on the concentration and relaxation calculated by α and β waves during the experimental process, which is one of the methods used for evaluating physiological changes.

The heart rate varies according to the sex, age, and physiological status of each body [69]. For example, the heart rate of a baby can be as high as 130 bpm, while the heart rate of a woman is slightly faster than that of a man. Heart rate variability measures the variability of the interval between two heartbeats and is an indicator of the balance of body control, which is widely considered to reflect the body's activity [70]. The heart rate data of this experiment was measured by the Xiaomi heartbeat bracelet, and the relative error was 5%. The data interval was once per minute, and the measurement time of each round was 60 min.

3. Results

3.1. Influence of Lighting on Subjective Psychological Evaluation

For subjective psychological evaluation, the answers to each questionnaire were statistically studied, and the correlation of each lighting environment was analyzed by an independent sample *T*-test. This paper-based questionnaire mainly assessed their subjective feelings about each lighting condition. Table 2 shows the significance of the *T*-test in each lighting condition. The results of comfort and relaxation level in CCT and illumination were clearly correlated. Since the relaxation level tendency is similar to that of the comfort level, the comfort level and thermal sensation vote are also shown in Figure 3.

Table 2. Significant (p) results of T-test for subjective psychological evaluation.

Subjective Psychological Evaluation	CCT			Illumination			EML
	3000 K 4000 K	4000 K 5500 K	3000 K 5500 K	<200 lux 200~500 lux	<200 lux >500 lux	200~500 lux >500 lux	<150 EML ≥150 EML
Self-evaluative work performance	0.343	0.474	0.308	0.499	0.397	0.411	0.109
Mental state	0.327	0.024 *	0.063	0.187	0.388	0.169	0.112
Satisfaction with CCT	0.280	0.184	1.65	0.036	0.105	0.497	0.037 *
Satisfaction with illumination	0.105	0.309	0.039 *	0.380	0.477	0.388	0.280
Relaxation level	0.002 **	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	0.002 **	0.443
Comfort level	0.002 **	0.004 **	<0.001 ***	0.003 **	<0.001 ***	0.073	0.367
Thermal sensation	0.060	0.086	0.001 **	0.075	0.150	0.025	0.232

Note: $p < 0.05$ is marked with *; $p < 0.01$ with **; $p < 0.001$ with ***.

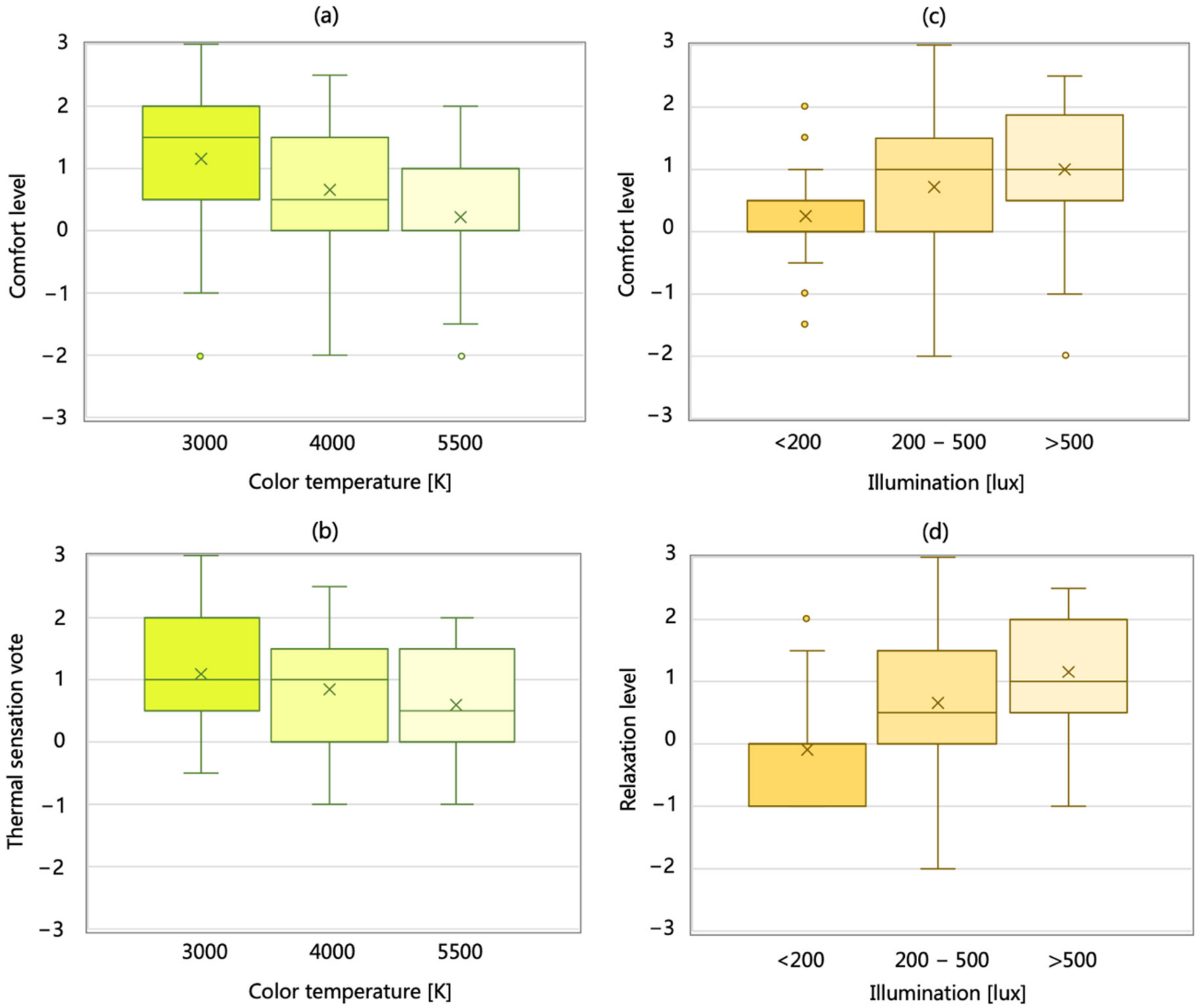

Figure 3. Comfort level and thermal sensation votes of different CCTs and illumination: (**a**) The comfort level of subjects under different CCTs; (**b**) The difference in psychological evaluation of thermal sensation under different CCTs; (**c**) The comfort level under different levels of illumination; (**d**) The relaxation level under different levels of illumination.

First of all, three kinds of CCTs—3000 K, 4000 K, and 5500 K—were used to make a detailed classification of psychological evaluation. Figure 3 shows the factors with obvious correlation and change in this section. Figure 3a shows the comfort level of subjects under different CCTs. With significance, comfort level reached the highest value at 3000 K and decreased with the increase of CCT. Relaxation levels demonstrated a similar tendency. This result was consistent with the study of Sheedy et al. [71]. The higher illumination could reduce the sensations of discomfort. Figure 3b shows the difference in psychological evaluation of thermal sensation under different CCTs. During the experiment, the physical air environment was kept the same, but the subjects felt warmer at 3000 K than at 5500 K.

We then applied three groups of horizontal illumination to explore the influence of illuminance on the psychological evaluation. Figure 3c shows the comfort level under different levels of illumination. It is notable that illumination above 500 lux was the most comfortable lighting, while values less than 200 lux had the worst results. At the same time, in the relaxation contrast of Figure 3d, the relaxation level increased with the increase of illumination and achieved the highest value when greater than 500 lux.

3.2. Influence of Lighting on Work Productivity

For work productivity, all of the ASL, DAKT, and Sudoku answers were statistically analyzed according to CCT, illumination, EML, and psychological satisfaction. The work productivity test was conducted on paper (Sudoku) and computer (ASL, DAKT). Some studies had proved a strong relationship between computer or paper-based visual tasks and lighting conditions [29,71]. This study integrated these two tasks in proportion, considering the relationship between comprehensive productivity and lighting conditions. Table 3 shows the significance of the independent sample *T*-test for each lighting condition.

Table 3. Significant (p) results of *T*-test for work productivity evaluation in CCT.

Work Productivity Evaluation	**CCT**			**Illumination**			**EML**	**Lighting Satisfaction (EML ≥ 150)**
	3000 K 4000 K	**4000 K 5500 K**	**3000 K 5500 K**	**<200 lux 200~500 lux**	**<200 lux >500 lux**	**200~500 lux >500 lux**	**<150 EML ≥150 EML**	**Satisfied Unsatisfied**
Self-evaluative work performance	0.179	0.332	0.238	0.107	0.003 *	0.012 *	<0.001 ***	0.034 *

Note: $p < 0.05$ is marked with *; $p < 0.01$ with **; $p < 0.001$ with ***.

Figure 4a shows the effect of CCT on work productivity. The results showed that the correct rate of personnel tests was 98.46% in 3000 K, 98.60% in 4000 K, and 98.60% in 5500 K, demonstrating that CCTs have no significant influence on productivity. On the other hand, Figure 4b shows the effect of illuminance on work productivity. When the illumination was above 500 lux, the working efficiency was the best, which revealed an increasing trend with the increase of illumination. Figure 4c shows the effect of sufficient and insufficient 150 EML on work efficiency. Of note, the working efficiency of the subjects in the light situation with enough 150 EML was better than that in the light situation with insufficient 150 EML, and the test accuracy was 98.87%, with a statistically significant difference ($p < 0.0001$).

Figure 4d shows the effect of a comfortable lighting environment on productivity under the condition of sufficient 150 EML. The evaluation of lighting comfort is based on comprehensive factors such as light color, illumination, and uniformity. In this study, the classification method of lighting-environment comfort consisted of the subjects filling out the questionnaire in which lighting comfort has a value greater than 0. In contrast, if the lighting comfort was less than or equal to 0, all such values were classified as uncomfortable. The results showed that the working efficiency of the comfortable lighting situation was significantly better than that of the uncomfortable lighting situation ($p < 0.05$), and the average correct rate of the sufficient condition was as high as 99.01%, while the average correct rate of the insufficient one was only 98.63%.

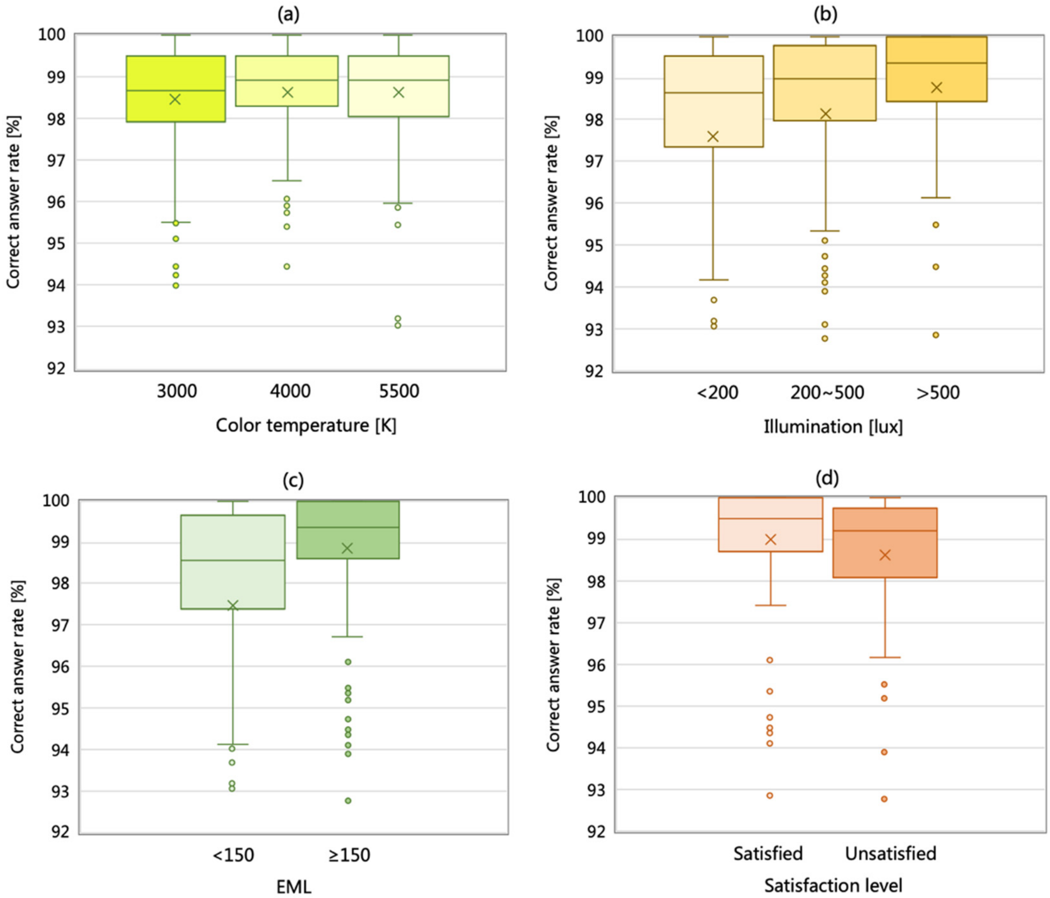

Figure 4. Correct answer rates of different CCTs, illumination, EML, and satisfaction level: (**a**) The effect of CCTs on work productivity; (**b**) The effect of illuminance on work productivity; (**c**) The effect of sufficient and insufficient 150 EML on work efficiency; (**d**) The effect of a comfortable lighting environment on productivity under the condition of sufficient 150 EML.

3.3. Influence of Lighting on Physiology

In this section, the data from a simple brain wave instrument and the smart bracelet were analyzed to evaluate the effects of lighting on human physiology. These instruments recorded the brain-wave and heart-rate data of the subjects in various light conditions. Then, the brain wave and heart rates of the subjects under each light condition were averaged to eliminate the interference of different tasks. The lighting situation was distinguished by CCT, illumination, and EML. Table 4 shows the correlation of physiological change data under each situation analyzed by the independent sample *T*-test. The results of the *T*-test showed that no significant differences in brain waves and heart rates were observed in different EML, CCT, and light conditions.

Table 4. Significant (*p*) results of *T*-test for physiological changes evaluation.

Physiological Changes Evaluation	**CCT**			**Illumination**			**EML**
	3000 K 4000 K	**4000 K 5500 K**	**3000 K 5500 K**	**<200 lux 200~500 lux**	**<200 lux >500 lux**	**200~500 lux >500 lux**	**<150 EML ≥150 EML**
Concentration level of brain wave	0.195	0.201	0.466	0.390	0.440	0.465	0.411
Changes of heart rate	0.087	0.206	0.285	0.447	0.383	0.317	0.212

Note: $p < 0.05$ is marked with *; $p < 0.01$ with **; $p < 0.001$ with ***.

Figure 5a,b show no significant difference in brain waves under different CCT and illumination conditions. The average values of the concentration level in each lighting environment were maintained at 49. When the CCT was at 5500 K, the average value of concentration level was relatively higher than others. Meanwhile, the values of the concentration level of each subject were similar in the conditions of CCT at 3000 K and illuminance higher than 500 lux. In Figure 5c, the heart rate of subjects changed considerably in different CCTs, which reached the highest average value of 78 bpm when the CCT was 4000 K. On the other hand, in Figure 5d, under different illumination conditions, the average heart rate value was approximately 77 bpm. However, the change range of heart rate was larger with the increase of the illumination. Therefore, although the relationship between light conditions and physiological change was not obvious, the heart rate could offer additional research opportunities with regard to adjustable lighting mode.

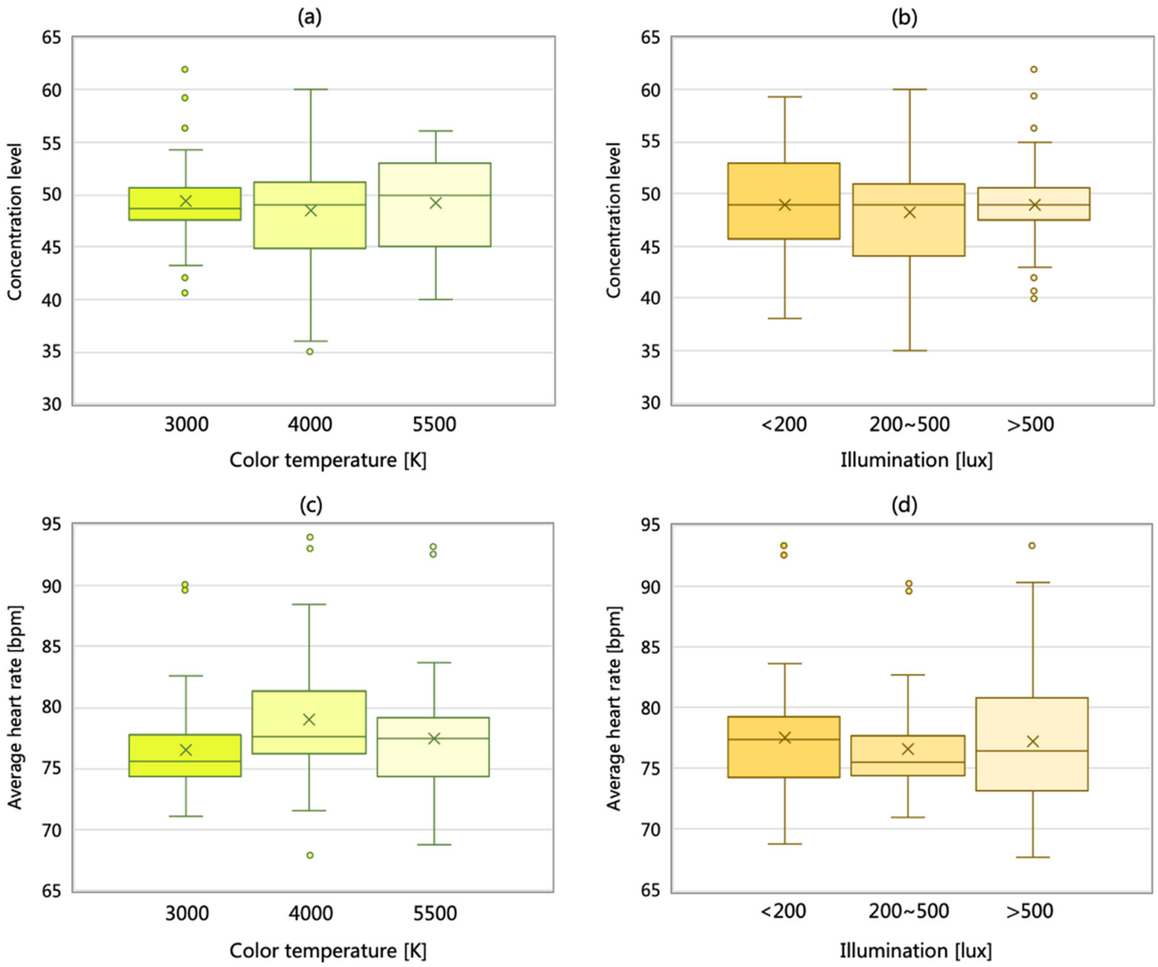

Figure 5. Concentration level and average heart rate of different CCTs and illumination: (**a**) The difference in brain waves under different CCTs; (**b**) The difference in brain waves under different illumination; (**c**) The heart rate of subjects under different CCTs; (**d**) The heart rate of subjects under different illumination.

3.4. Influence of Adjustable Lighting

In the adjustable lighting part, the illuminance and CCT were adjusted by 35 subjects with two different initial lighting settings. As shown in Figure 6a, two kinds of initial setting values of horizontal illumination were available—high and low, with values of 730 lux and 100 lux, respectively. The average values of self-adjusted horizontal illumination were 502 lux in the high initial illumination situation and 457 lux in the low initial illumination situation. Therefore, the two different lighting conditions had similar adjusted horizontal illumination values.

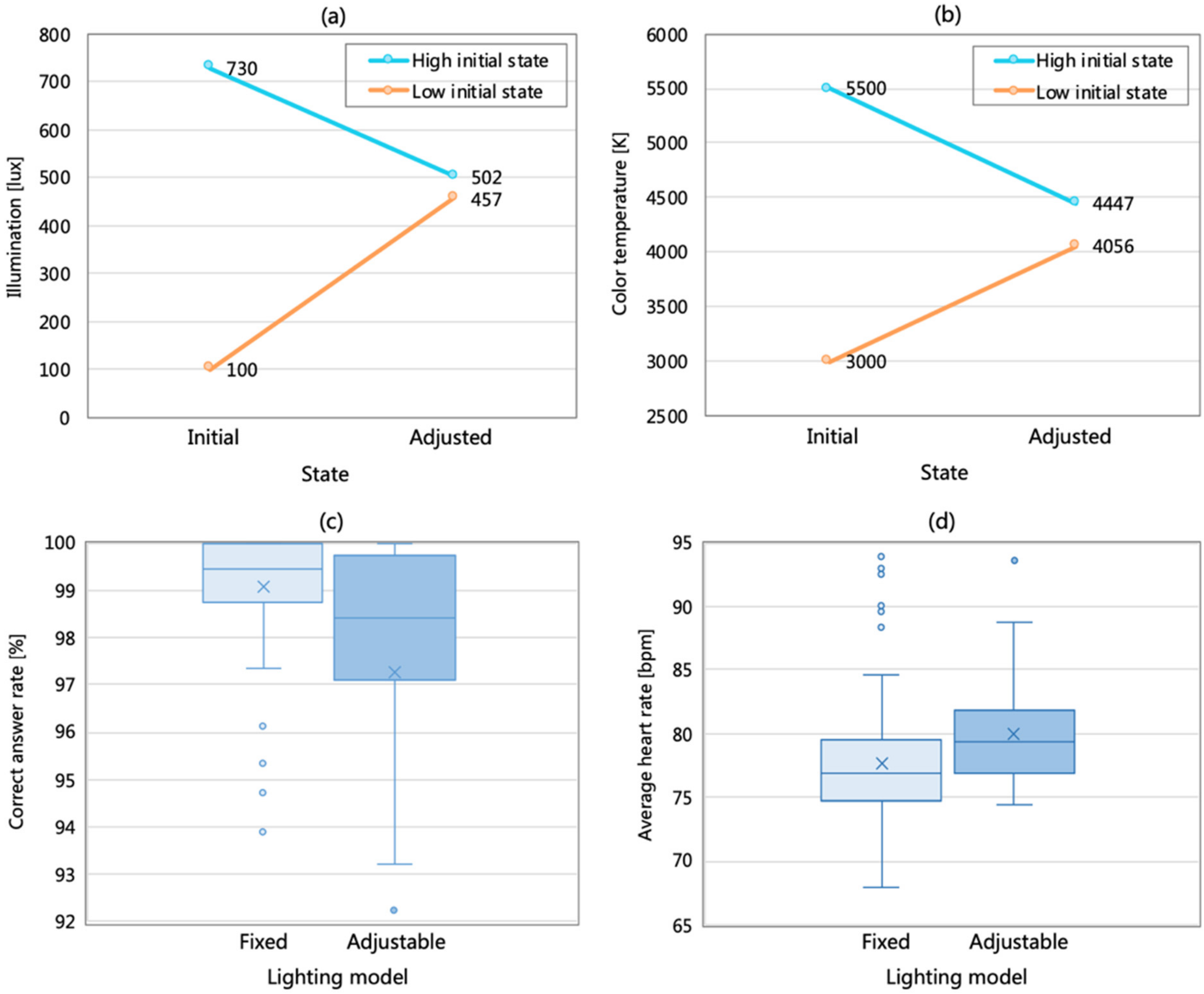

Figure 6. Illumination and CCT in different states of adjusted lighting and answer rate and average heart rate in fixed and adjusted state: (**a**) Illumination in different states of adjusted lighting; (**b**) CCTs in different states of adjusted lighting; (**c**) The correct answer rates in fixed and adjusted state; (**d**) The average heart rates in fixed and adjusted state.

CCT had two kinds of initial setting values—5500 K and 3000 K. Figure 6b shows the final CCT values adjusted by the subjects at two different initial CCT settings. Under the light condition of high initial CCT, the self-adjusted average value of subjects was 4447 K, while the low initial one ultimately reached 4056 K. Like illumination, the linear relationship between the high initial CCT and the low initial CCT did not differ considerably.

In Table 5, the results of the independent sample *T*-test show no significant difference in psychological evaluation between adjustable and fixed lighting but do indicate a significant difference in actual work productivity and heartbeat change. Figure 6c shows that work efficiency was significantly improved under fixed lighting, with an average accuracy of 99.09%, which dropped to 97.26% in the controllable state. Meanwhile, Figure 6d shows that the heart rate was lower in the fixed lighting, with an average value of 77.67 bpm, and faster in the adjustable lighting, with an average value of 80.01 bpm.

Table 5. Significant (p) results of T-test for adjusting lighting in psychological, physiological, and productivity evaluation.

Adjustable Lighting	Satisfaction with CCT	Satisfaction with Illumination	Comfort Level of Lighting	Self-Evaluative Productivity	Actual Productivity	Average Brain Wave	Average Heat Rate
Significant value (p)	0.052	0.243	0.194	0.298	<0.001 ***	0.216	0.006 *

Note: $p < 0.05$ is marked with *; $p < 0.01$ with **; $p < 0.001$ with ***.

3.5. Lighting Energy Consumption

The lamp used in this experiment is a controllable light-emitting diode (LED), which features the advantages of variable CCT and illuminance, high energy conversion efficiency, small size, and long service duration. The disadvantage was that the luminosity of LED was not linear with the current, so adjusting the luminosity was slightly complicated. By controlling the amount of current, the lamp could change the degree of lighting and produce different illumination values. The energy consumption information in the experiment was called out from the smart lighting system, including illuminance, CCT, currency, and lighting power. Through analysis, CCTs had little influence on energy consumption, and a positive linear correlation between illuminance and energy consumption was found in Figure 7. As a result, when the horizontal illumination was 500 lux, the lighting power was about 10 W, and when the horizontal illumination was 900 lux, the lighting power was about 20 W. Thus, the relationship between the energy consumption of lighting and illumination can be concluded as a formula, and the further discussion of the lighting control strategy for energy-saving will be proposed in the next section.

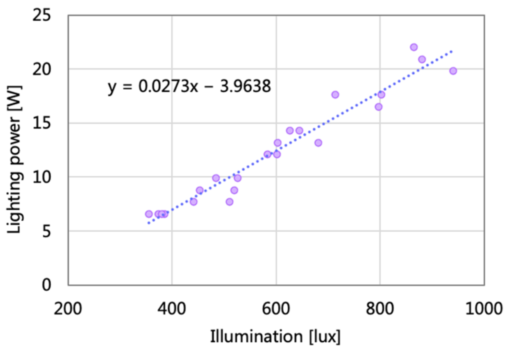

Figure 7. Tendency of illumination and energy consumption.

4. Discussion

4.1. Comprehensive Analysis of Light Environment, Psychological Evaluation, and Productivity

Based on the T-test results in the previous section, the correlation of each lighting characteristic with influence on psychology, physiology, and productivity in this study could be concluded. We measured the physiological states of heart rate and brain-wave concentration of the subjects during the experiment, but no significant difference in physiological effects was observed in any of the lighting conditions; only adjustable lighting caused a slight increase in heart rate. It also indicated that no extreme or inhumane situation setting was present in the experiment, and people were not nervous or distracted. Meanwhile, the experimental results showed that CCT and illumination had psychological effects, such as comfort and relaxation levels. However, the EML and adjustable lighting mode did not have a close correlation with psychological influence based on the experiment. Furthermore, work productivity was significantly correlated with lighting characteristics, including illumination, EML, and adjustable lighting mode, but it was not influenced a lot by CCT. In conclusion, based on the experimental results, the CCT influenced the psychological results, while the illumination could affect both psychology and productivity.

EML had a close relationship with productivity, and the adjustable lighting mode correlated with physiology and productivity.

4.2. Lighting Control Strategies under Different Conditions

4.2.1. Lighting Control Strategy Based on User Preference

From the perspective of occupants' psychological evaluation, the best combination for uncontrollable lighting situations was CCT at 3000 K and illumination of 500 lux or above. For the adjustable lighting situation, the optimal setting was approximately CCT at 4200 K and illumination of 500 lux. Although both the controllable and uncontrollable lighting needed almost 500 lux for the best horizontal illumination, their results in CCT were quite different. Therefore, we suggest that in the user-controlled mode, 4200 K CCT and 500 lux horizontal illumination are taken as the preset values. Moreover, the memory controller should be added to enable the lighting system, and the last value adjusted by the user should be recorded, which could improve convenience and reduce adjustment frequency. Meanwhile, in the uncontrollable mode, the suggested settings for CCT and horizontal illumination are 3000 K and 500 lux, respectively.

4.2.2. Lighting Control Strategy Based on High Productivity

According to the experimental results, CCT does not significantly affect the objective efficiency performance, which obtained a slightly higher correct answer rate at 4000 K. Illumination is the most important parameter for work productivity. Furthermore, the biggest influence factor (EML) is a part of illumination. Therefore, the illumination value is the main consideration for a high-productivity lighting control strategy. In addition, in comparing different EML conditions, it can be found that sufficient EML is closely related to high productivity, which could also increase satisfaction levels. Therefore, for a high-efficiency lighting control strategy, the illumination level must be more than 500 lux, with a sufficient amount of 150 EML, and the user's comfort is improved as much as possible.

4.2.3. Lighting Control Strategy Based on Healthy Light Environment

Although the results in the *T*-test showed no significant correlation between physiological data and lighting conditions in Table 5, the adjustable lighting mode is still recommended for a healthy light environment since the controllable lighting has a relationship with heart rate, as shown in Figure 6. Our proposal for a healthy lighting control strategy is shown in Figure 8, in which the experimental results and WELL regulations are combined. Between 09:00 and 13:00, each seat should reach a sufficient value of 150 EML, which could reduce daytime sleepiness. Furthermore, it is recommended to reduce the value after 20:00 to minimize the eyes' absorption of blue light. Since illumination and CCT did not significantly influence physiological indices, we suggest no special CCT or illumination requirements at 13:00 to meet the lighting requirements of daily operations.

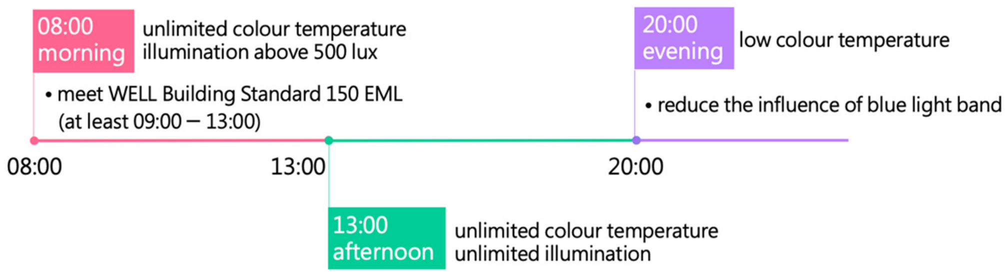

Figure 8. Proposal for healthy lighting control strategy.

4.2.4. Lighting Control Strategy Based on Energy-Saving

If energy-saving and carbon reduction are considered demands of the lighting control strategy, the main influence factor of energy consumption is illuminance value. Therefore, for energy-saving lighting, the design purpose is to reduce the illumination value as much as possible while ensuring normal operations can be carried out without limitation. Figure 4b shows the relationship between the horizontal illumination value and work productivity. Illumination above 500 lux has the highest work efficiency. The formula in Figure 7 shows that the power of the horizontal illuminance of 590 lux is about 12.1 W, while that of the horizontal illuminance of 450 lux is about 8.8 W. Therefore, decreasing the horizontal illumination from 590 lux to 450 lux can save 3.9 W energy power of each lamp but may also lose 0.83% of each person's productivity.

Therefore, we recommend using intermittent lighting to save energy and prevent user discomfort caused by extreme reduction of lighting and energy consumption. For example, applying the lighting energy-saving mode for 5–10 min each hour can satisfy both energy-saving and occupant comfort needs. In addition, the lighting system can also be combined with an outdoor real-time monitoring illumination system to adjust the artificial light source in real-time by daylight in order to achieve the effect of energy reduction and carbon reduction.

4.3. Comprehensive Lighting Control Strategies

Since most practical applications are considered using comprehensive factors, this section combines the feasibility and practicability of the previous four lighting control strategies to provide suggestions regarding comprehensive lighting control strategies for an office space working 8 h a day. Detailed descriptions of the three lighting control strategies are proposed below. In this part, various factors were considered to develop comprehensive office lighting strategies. On the one hand, because this experiment was conducted in the daytime, the subjects' physiological and psychological time was in the daytime. On the other hand, this study mainly provided recommendations for office lighting strategies. Therefore, the comprehensive office lighting strategies in this study were mainly from 8:00 to 17:00.

4.3.1. Fixed Lighting Control Strategy Based on Productivity and Circadian Rhythm

According to the experimental results, the work efficiency of the personnel with uncontrollable lighting is better than that of those with controllable lighting. Therefore, the lighting control strategy of work productivity and circadian rhythm mainly focuses on uncontrollable lighting, with some adjustments based on circadian lighting and workers' rest time. Figure 9a shows the daily schedule of work efficiency and circadian-rhythmic lighting control strategy in fixed lighting mode.

From 8:00 to 12:00, it is necessary to maintain the illumination level above 500 lux, and the illumination of melatonin should be higher than 150 EML. Furthermore, the suggestion for CCT is to maintain it within the range of middle to the high level, between 4000 K and 5500 K, which not only makes people feel refreshed and bright but also ensures that the mechanism for inhibiting melatonin is activated. At 12:00, the CCT should be adjusted to 3000 K for a more relaxed and comfortable rest environment at break time. In order to maintain 150 EML, the horizontal illumination should be increased to 590 lux. At 13:00, the schedule returned to the same working light setting as at 08:00. After 15:00, when the workday is about to end, to avoid the situation of high-cold color and warm light all day without proper rest, a more comfortable and relaxed light situation can be provided at the end of the lighting schedule. At this time, the CCT can be reduced to warm or intermediate color, from 3000 K to 4000 K, while illumination can be maintained above 500 lux.

4.3.2. Adjustable Lighting Control Strategy Based on Productivity and Circadian Rhythm

When considering the actual use of personalized lighting, due to the great differences in personal preferences, adjustable lighting may also be applied. Therefore, although the productivity of uncontrollable lighting is better than that of controllable lighting, the lighting control strategy of work efficiency and circadian rhythm can also mainly use an adjustable lighting mode, in which adjustments are made according to the requirement of circadian lighting and the rest time of personnel. Figure 9b shows the control strategy of work productivity and circadian rhythm with adjustable lighting.

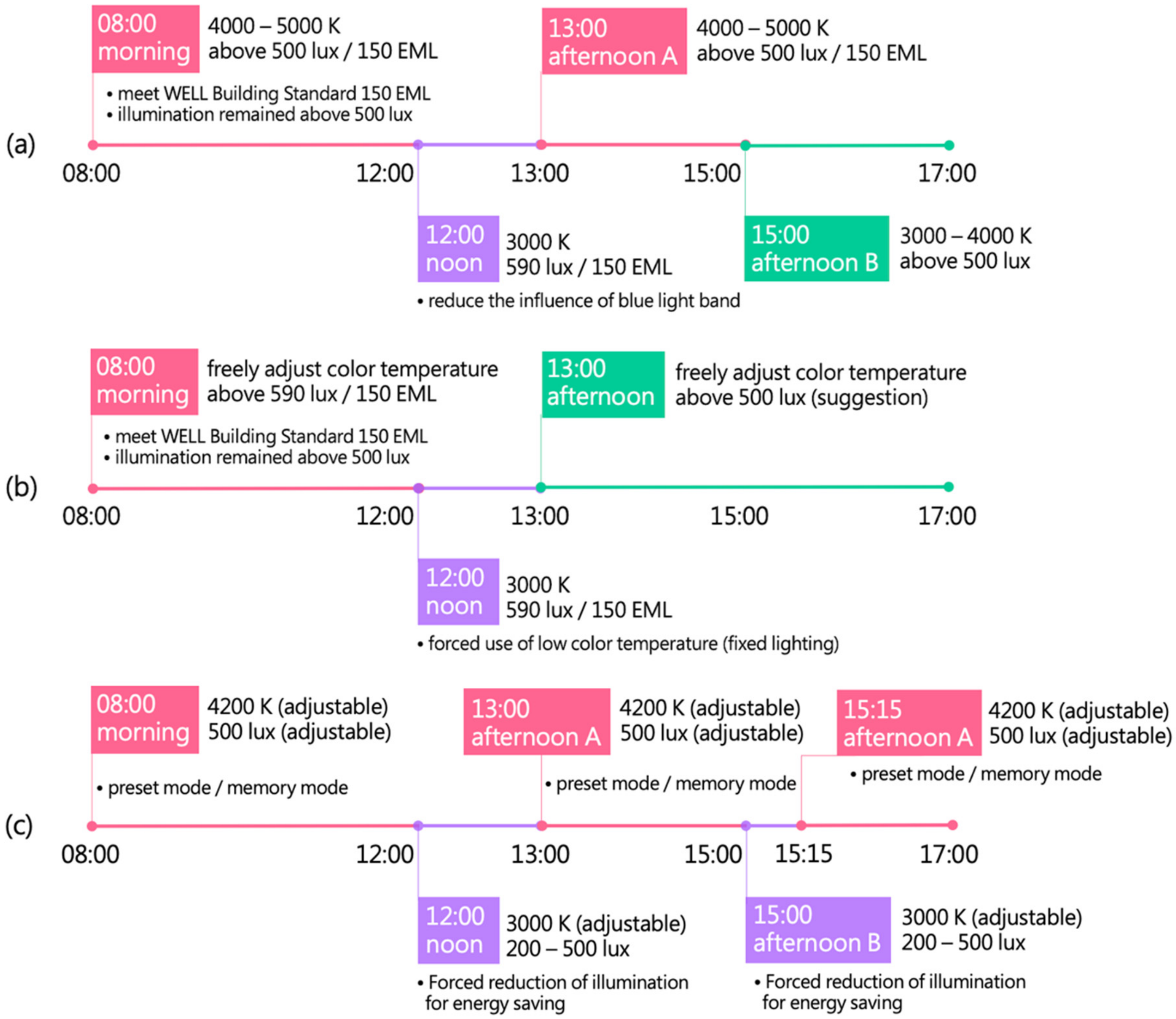

Figure 9. Comprehensive lighting control strategies: (**a**) Fixed lighting control strategy based on productivity and circadian rhythm; (**b**) Adjustable lighting control strategy based on productivity and circadian rhythm; (**c**) Adjustable lighting control strategy based on psychology and energy-saving.

The CCT between 8:00 and 12:00 in the morning can be freely adjusted by the user, but the horizontal illumination value should be maintained above 590 lux to ensure that the user can still reach the standard of 150 EML even when the CCT is adjusted to 3000 K. During the rest period from 12:00 to 13:00, the lighting cannot be controlled for one hour, and the light situation is set with CCT of 3000 K and horizontal illumination of 590 lux, which provides a more comfortable rest situation for personnel while simultaneously meeting the 150 EML standard. After 13:00, meeting the 150 EML requirement is no longer mandatory so that the users can control the CCT and illumination value according to their own habits and preferences. It is suggested that the user interface can show melatonin illuminance value for CCT and illuminance control, which can provide a reference for workers to adjust the lighting value.

4.3.3. Adjustable Lighting Control Strategy Based on Psychology and Energy-Saving

This lighting control strategy is based on psychological satisfaction, adjustable lighting, and energy-saving, as well as personnel rest. From the users' view, we recommend adding the preset or memory mode into the lighting system to improve the convenience of workers. In the preset mode, the preset values of the lighting lamps are adjusted according to the experimental results and thus have the CCT of 4200 K and horizontal illumination of 500 lux. In memory mode, the system will record the CCT and illumination value adjusted by the user. When the light is on, the last set value will be displayed again as a preset value, which can improve psychological satisfaction. Meanwhile, when people rest and do not pursue high efficiency, energy-saving lighting can be applied to save energy by reducing the illumination for a short time. Figure 9c shows the schedule of a satisfactory, adjustable, and energy-saving lighting control strategy.

In the morning, the light is turned on between 8:00 and 12:00. The preset values of the CCT and horizontal illumination are 4200 K and 500 lux, respectively. At the same time, users can adjust the light color and illumination according to their preferences. At the break time of 12:00 to 13:00, the CCT will be automatically reduced to 3000 K with high satisfaction, and the illumination will also be compulsorily decreased below 500 lux. At this time, the user can only adjust the CCT. Between 13:00 and 15:00, the lighting control returns to the same values as 8:00, and users can independently adjust the light color and illumination. During the afternoon break time from 15:00 to 15:15, the same control mode as noon is applied. The system is forced to reduce the level of illumination to below 500 lux for energy-saving. After 15:15, the preset value of lighting returns to 4200 K and 500 lux. Users can also adjust the light color and illumination according to their preferences.

5. Conclusions

In this study, we performed light experiments with 67 subjects in Taiwan and researched the effect of CCT and illuminance on physiology, psychology, and productivity. In addition to the experiment results, the research also proposed control strategies under different requirements. There are main conclusions from this experiment:

- Psychological part: people prefer warm colors and bright lighting. The most comfortable and relaxed light situation was at 3000 K with warm color, which has a low value in the CCT range. Furthermore, the most comfortable degree of illumination was found to be 590 lux. The reason for the highest evaluation was that the luminance of 590 lux was sufficient but not dazzling. This level of illumination could significantly promote both subjective and objective alertness and have a positive effect on maintaining concentration and relaxation;
- Productivity part: although different CCT values did not affect staff performance, illumination had a great influence on work efficiency. The productivity in the light situation with horizontal illumination above 500 lux was significantly better than in others. Moreover, the illuminance value has a direct effect on the illuminance of the anti-melanin hormone. Therefore, the working efficiency of the staff with enough 150 EML is significantly better than that of an insufficient level of 150 EML;
- Adjustable lighting: the average CCT and illumination adjusted by the user were about 4200 K and 480 lux, respectively. The controllable lighting did not improve user satisfaction or self-evaluated efficiency, and the productivity was lower than that of the fixed lighting. Furthermore, the heart rate with adjustable lighting was greater than the fixed one. Finally, we proposed three lighting control strategies based on psychology, productivity, circadian rhythm, and energy-saving.

This study also has some limitations. In the experiment, we took 60 min as a unit and compared the lighting effects on human physiology, psychology, and work efficiency. However, human beings are constantly and closely related to their light environment. If the experimental time could be expanded, such as a working environment of eight hours a day, and even with the behavior pattern of night lighting added, the experimental results may be closer to the real situation. Future work should be carried out in a field office to verify the reproducibility of the experimental results by combining the prototype theory in the laboratory with daylight, as well as to provide more detailed suggestions for lighting control strategies in actual offices.

Author Contributions: Conceptualization, Y.-S.T. and M.-C.T.; methodology, Y.-S.T.; software, R.C.; validation, R.C.; formal analysis, Y.-S.T.; investigation, M.-C.T.; resources, Y.-S.T.; data curation, R.C. and M.-C.T.; writing—original draft preparation, R.C. and M.-C.T.; writing—review and editing, R.C.; visualization, R.C. and M.-C.T.; supervision, Y.-S.T.; project administration, Y.-S.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Human Research Ethics Committee of National Cheng Kung University (Approval number: No. NCKU HREC-E-108-359-2).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Acknowledgments: This research was partially supported by Delta Electronics, Inc.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Detailed Contents of the Psychological Evaluation Questionnaire

I. Work performance: (single choice)

1. Do you think the lighting environment is suitable for work? Very unsuitable/Unsuitable/Slightly unsuitable/Neither suitable nor unsuitable/Slightly suitable/Suitable/Very suitable.
2. How do you find concentrating on your work in this lighting environment? Very difficult/Difficult/Slightly difficult/Neither difficult nor easy/Slightly easy/Easy/Very easy
3. What do you think of your "work performance" in this lighting environment? Very bad/Bad/Slightly bad/Neither bad nor good/Slightly good/Good/Excellent.

II. Karolinska sleepiness scale

4. Please choose the description that best describes your current state. Very sleepy, need to work very hard to stay awake/Sleepy, but it takes just a little effort to stay awake/Sleepy, but don't need to work hard to stay awake/Slightly sleepy/Neither alert nor sleepy/Slightly alert/Alert/Very alert/Extremely alert.

III. Light environment quality: (single choice)

5. What do you think of the "luminance of the desktop"? Extremely dark/Dark/Slightly dark/Neither dark nor bright/Slightly bright/Bright/Extremely bright.
6. What do you think of the "luminance of the screen"? Extremely dark/Dark/Slightly dark/Neither dark nor bright/Slightly bright/Bright/Extremely bright.
7. What do you think of the "glare level" of this lighting environment? Very unserious/Unserious/Slightly unserious/Neither serious nor unserious/Slightly serious/Serious/Very serious.
8. What do you think of the "overall luminance distribution" of this lighting environment? Very uneven/Uneven/Slightly uneven/Neither even nor uneven/Slightly even/Even/Very even.

IV. Light environment sensation: (single choice)

9. How satisfied are you with the lighting environment? Very dissatisfied/Dissat isfied/Slightly dissatisfied/Neither satisfied nor dissatisfied/Slightly satisfied/Satisfied/Very satisfied.
10. How satisfied are you with the lighting environment with regard to luminance? Very dissatisfied/Dissatisfied/Slightly dissatisfied/Neither satisfied nor dissatisfied/Slightly satisfied/Satisfied/Very satisfied.

11. What do you think of the "light color acceptability" of this lighting environment? Very unacceptable/Unacceptable/Slightly unacceptable/Neither satisfied nor dissatisfied/Slightly acceptable/Acceptable/Very acceptable.
12. What do you think is the "acceptable luminance" of the lighting environment? Very unacceptable/Unacceptable/Slightly unacceptable/Neither satisfied nor dissatisfied/Slightly acceptable/Acceptable/Very acceptable.

V. Emotional impact: (single choice)

13. How much do you think this lighting environment will "affect your mood"? Very unaffected/Unaffected/Slightly unaffected/Neither affected nor unaffected/Slightly affected/Affected/Very affected.
14. How do you feel in this lighting environment? Very nervous/Nervous/Slightly nervous/Neither nervous nor relaxed/Slightly relaxed/Relaxed/Very relaxed.
15. How do you feel in this lighting environment? Very uncomfortable/Uncomfor table/Slightly uncomfortable/Neither comfortable nor uncomfortable/Slightly comfortable/ Comfortable/Very comfortable.

VI. Light environment and color temperature: (single choice)

16. How do you feel about the light and color of the current lighting environment? Extremely cool color/Cool color/Slightly cool color/Neither cool nor warm color/Slightly warm color/Warm color/Extremely warm color.

VII. Indoor environment: (single choice)

17. How do you feel about the "temperature" of this space? Very uncomfortable/Uncomfortable/Slightly uncomfortable/Neither comfortable nor uncomfortable/Slightly comfortable/Comfortable/Very comfortable.
18. How do you feel about the "overall comfort" of the office space? Very bad/Bad/ Slightly bad/Neither good nor bad/Slightly good/Good/Excellent.

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