energies

Article

Strategies on Visual Display Terminal Lighting in Office Space under Energy-Saving Environment

Yusen Lin [1,*], Cheng-Chen Chen [2,*] and Yasser Ashraf Gandomi [3]

1 Department of Architecture, National United University, Miaoli 360301, Taiwan
2 Department of Architecture, National Taipei University of Technology, Taipei 106344, Taiwan
3 Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02142, USA
* Correspondence: linyusen@nuu.edu.tw (Y.L.); coolhas2000@gmail.com (C.-C.C.)

Abstract: In this work, we have studied how the vertical illuminance of the human eye position, illuminance of the horizontal work surface, and the brightness of the computer screen in the office space lighting are correlated under an energy-saving environment. This investigation was conducted in a full-scale laboratory that simulates an office space with 20 adults. It was found that when the indoor ambient lighting illuminance changes, the vertical illuminance of the subject's eye position is affected accordingly, and the two factors are strongly correlated. On the other hand, when the surrounding environment is brighter and the vertical illuminance increases, the illuminance of the horizontal working surface adjusted by the subject during the visual display terminal (VDT) operation is significantly reduced. The horizontal illuminance value can even be lower than the value frequently employed in various countries around the world, since the computer screen brightness will be adjusted accordingly. Therefore, in an energy-saving environment, the illuminance of the horizontal working surface and the brightness of the computer screen adjusted by the users will vary with the ambient lighting. Especially in the current mainstream VDT operating environment and within a certain range of conditions, the interior setting can be lower than the current horizontal illuminance benchmark for additional energy conservation.

Keywords: energy-saving; energy-saving strategies; VDT; indoor lighting space

check for updates

Citation: Lin, Y.; Chen, C.-C.; Ashraf Gandomi, Y. Strategies on Visual Display Terminal Lighting in Office Space under Energy-Saving Environment. *Energies* **2023**, *16*, 1317. https://doi.org/10.3390/en16031317

Academic Editors: Chun-Yen Chang, Teen-Hang Meen, Charles Tijus and Po-Lei Lee

Received: 13 December 2022
Revised: 20 January 2023
Accepted: 23 January 2023
Published: 26 January 2023

1. Introduction

Most human beings spend 90% of their life within indoor environments; thus, a good indoor environment will preserve human health and comfort [1,2]. Many studies have demonstrated that the quality of the environment significantly affects the quality of human life [3,4]. With the development of lighting research, the topic of environmental lighting has not only focused on the impact of artificial indoor lighting but also expanded to the effect of lighting on comfort and satisfaction [5–7]. Since the Great East Japan Earthquake in 2011, the nuclear leakage of the nuclear power plant has affected the energy policy of Japan and the entire world. Recently, the Russian-Ukrainian war in 2022 has caused the European energy crisis, leading to serious power shortages in Europe. Nowadays, China is a critical industrial country with major manufacturing centers located in Shanghai, Zhejiang, and Sichuan provinces. If power supply is interrupted in these cities, the industrial developments and business activities will hugely be affected. Therefore, before the full adoption of the renewable energies, strict power saving policies must be implemented. According to the analysis of the 2021 energy audit annual report released by the Energy Bureau of the Ministry of Economic Affairs of Taiwan, the major energy-consuming equipment in domestic office buildings are air-conditioning units (56.42%), lighting equipment (13.34%), office electronics (9.81%), and elevators (7.25%). Thus, the energy-saving efforts in buildings has primarily focused on optimizing the energy consumption within the air conditioning and lighting equipment.

The lighting environment has been proven to have a significant impact on people's life and health [8]. Several strategies have been explored for energy-saving in a lighting environment, including the use of LED lights with daylighting or occupancy controls [9]. At present, the office lighting standards around the world mostly take the illuminance of the horizontal working surface as the main recommended value (300–750 lux, as shown in Table 1) [10,11].

Table 1. Office illuminance standards.

Office Illuminance Standard	Country	Illuminance (lux)
JIS Z9110:2011	Japan	500–750
CNS 12112	Taiwan	300–750
GB 50034-2004	China	300–500
CHNII23-05-95	Russia	300
SFS-EN 12461-1:2011	EU	500

Recently, in office environments, the major focus of the users has changed from writing/reading paper documents to operating computers, reading electronic articles, and other visual display terminal (VDT) workstation activities [12,13]. Considering the VDT work mode as an example, the worker's sight is no longer focused on the horizontal desktop. The need for the detailed reading of documents or drawing has been gradually replaced by additional computer work. Currently, the sight of the worker's personal office area is mainly vertical. The computer screen is the main source of light, so most of the light received by the eyes comes from the luminous brightness of the computer screen, the light around the space, and the reflection of the desktop. Indeed, the effect of appropriate lighting on the work efficiency should be a critical point to consider in working environments [14].

A limited number of prior works have reported on the influence of low illumination in the office environment on power saving. Liu et al. found that when the brightness of the computer screen is 30 cd/m^2, 200 lux horizontal working surface illumination has a higher work efficiency to alleviate the visual fatigue than 500 lux [15]. The Architectural Institute of Japan (AIJ) conducted a survey on the office lighting environment during the power outage period in Tokyo in 2011. When the illuminance of the horizontal working surface was 200–300 lux, 40% of the workers felt unbright and dissatisfied; whereas increasing the horizontal desktop illuminance value to 300–400 lux resulted in ~35% dissatisfaction among the users [16,17]. Despite the increase in horizontal illumination, the satisfaction level did not increase. There are few other studies conducted in Taiwan on the vertical illuminance of the human eye, the illuminance of the horizontal work surface, and the brightness of the computer screen of the VDT workstation [18]. This paper aims to elaborate on the lighting control plan needed for a minimum horizontal allowable illuminance, optimal horizontal illuminance (HI), and the corresponding vertical illuminance (VI) for general VDT office workers in a shortage of power situation. To conduct the experiments, a full-scale laboratory (with no significant sunlight) was used to simulate an office space, and five different subjects' eye positions (from vertical illuminance) was chosen to represent the ambient background lighting. Herein, 20 adults (with no vision disabilities) participated as subjects to conduct the horizontal work surface illuminance. In the experiment of dimming and computer screen brightness adjustment, the users were asked to alter the minimum horizontal allowable illuminance and optimize the most comfortable level of illuminance via adjusting the horizontal working surface illuminance as well as the computer screen brightness.

Finally, this study collects questionnaires and experimental data, conducts correlation analysis and regression analysis, and finally suggests an optimal range of vertical illuminance along with horizontal illuminance. The originality of this research lies in two aspects: (i) the choice of minimum level allowable illuminance for VDT workers of Taiwan as the object, which represents the lighting strategy that can be recommended in the event of energy shortage and (ii) the interaction between ambient lighting and work surface lighting in order to provide the most efficient lighting environment.

2. Methodology

2.1. Overview

This study intends to simulate the actual office space as the test site to conduct the lighting control experiment, where the subjects were required to perform the lighting dimming experiment in the VDT working [19]. The light sources in this research were selected from the ambient lighting and work surface lighting, respectively. There were five fixed modules for the ambient lighting, while there was only a single work surface lighting. The users had the capability to adjust their own favorable lighting requirements for the work surface, ranging from 0 to 750 lux. The entire surface of the desk was used as the task area and the subjects were asked for the VDT work. During the experiment, the ambient lighting was used as a variable, and the subjects were required to control the illuminance of the working surface in two modes: minimum tolerance and comfortable satisfaction under various ambient lighting. Meanwhile, it was necessary to measure the vertical illuminance of the subject's eye position as well as the horizontal illuminance of the horizontal working surface. The flowchart including the details of this study is illustrated in Figure 1.

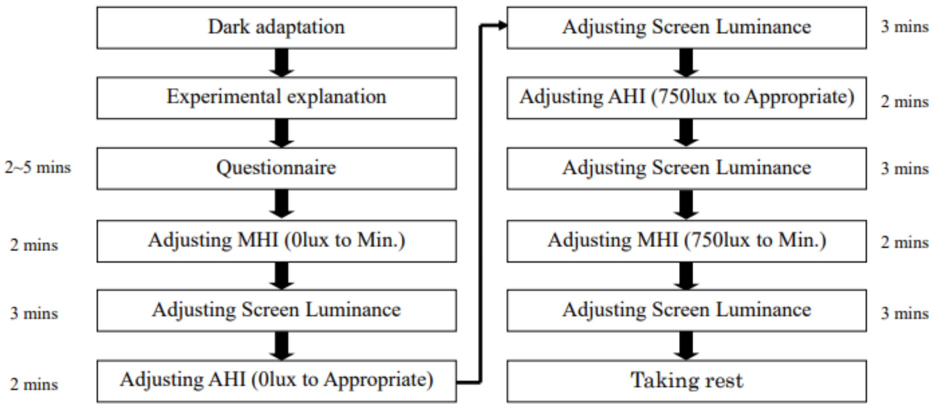
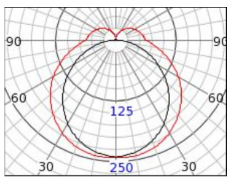
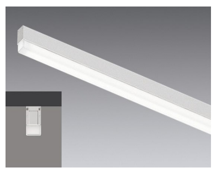


Figure 1. Flowchart for investigating the VDT illuminance strategy proposed in this study.

2.2. Field Study

The research laboratory where all the experiments of this study were performed was located in a room with no window and no sunlight. In this laboratory, there were linear tube LED that were employed to adjust the ambient lighting, and these lamps were not accessible to the subjects (participants) themselves. The lighting technical specifications is shown in Table 2.

Table 2. Lighting technical specifications.

Product	Technical Specifications	Light Distribution Curve	Pic.
Ambient and Task lighting Linear tube LED Endo ERK9708W	CCT: 4000K CRI: 82 Tilt angle: 0° Color: Cool White Wattage: 40 W		

The ambient lighting sources were placed on the ceiling in front of the desk area, and the researcher could use an adapter to control the power output from 5% to 100%. All the ambient lightings were the liner tube LED (Endo ERK9708W), which was concealed by the ceiling to avoid direct light affecting the subjects, as illustrated in Figure 2. The desk lighting system was similar to the ambient lighting and consisted of an adapter placed on the desk near the subject's right hand.

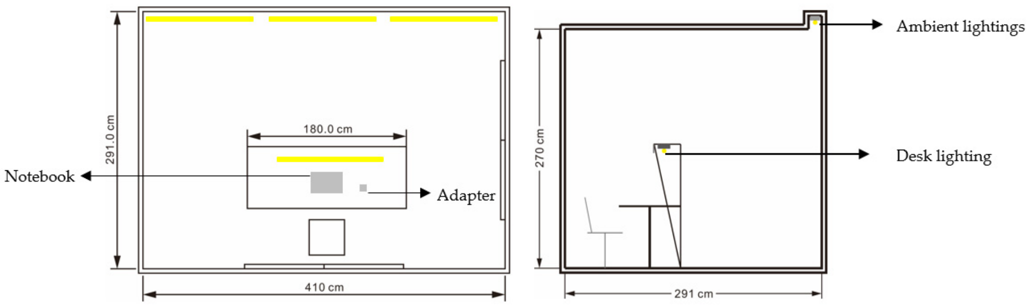


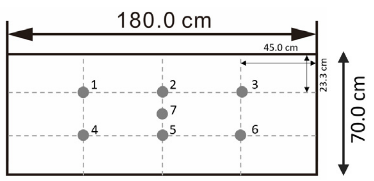
Figure 2. The layout of top-view and cross-sectional view testing space proposed in this study.

2.3. Measurement

2.3.1. Illuminance Measurement

There are 7 different points on the desk measured by the illuminance-meter (Konica Minolta T-10), as shown in Table 3. Each grid measures 45(L) × 23.3(W) cm. The No.7 point is the center of desk and located at the VDT keyboard and paper reading place. The measurement used an adapter to adjust the illuminance of No.7 at 50 lux, 100 lux, 150 lux, 200 lux and 250 lux. The average illuminance of these 7 points was very close to the illuminance of No.7. Because the desk lighting is indeed a linear light source, and the luminous intensity distribution curve was uniform here, the No.7 point was taken as the measurement point representing the horizontal illuminance. Vertical illuminance was measured in the subject's eye position (Height = 120 cm).

Table 3. Illuminance values measure in the task area.

Measure Point	No.1	No.2	No.3	No.4	No.5	No.6	No.7	Avg.
	52	55	53	46	51	48	50	51
	105	110	106	95	99	96	100	102
	155	160	155	139	145	142	150	149
	208	215	205	190	195	192	200	201
	258	265	260	238	245	241	250	251

2.3.2. VDT Screen Luminance Measurement

According to VESA FPDM standard (Flat Panel Display Measurements), using the luminance meter (TOPCON BM-910D, Topcon Positioning Systems, Inc., Tokyo, Japan), we measured the VDT screen at 9 various points and averaged the values to be the luminance of the VDT screen, as shown in Figure 3.

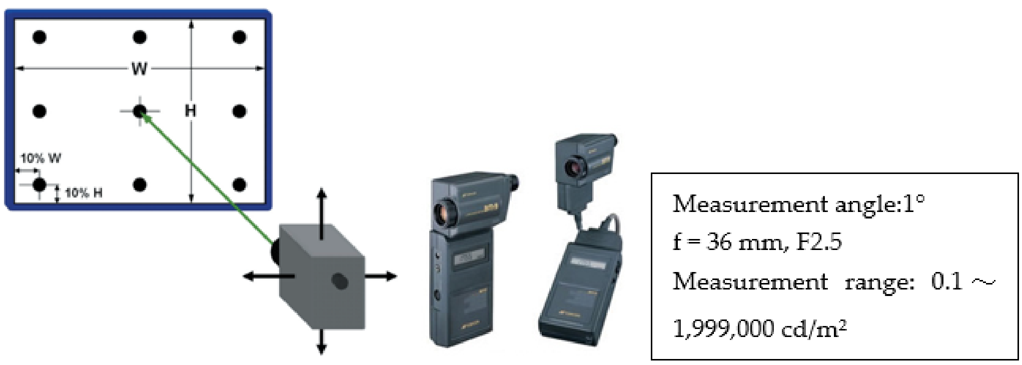


Figure 3. VESA FPDM standard for screen measurement and luminance meter.

2.3.3. Ambient Luminance

The ambient luminance pictures were recorded by a luminance camera, made by Kozo Keikaku Engineering Inc. (Tokyo, Japan) or a digital camera with a fisheye lens. The lens angles were 103.6° (right-left) and 76.5° (up-down), respectively. The luminance camera was set at 120 cm from the floor and located in subject's eye position for controlling the luminance distribution of the ambient lighting, including the average luminance of the space and uniformity of the luminance.

2.4. Experiment Arrangement

2.4.1. VDT Setting

All participants were asked to read an article shown on the VDT screen. The VDT station was a 14-in TFT-LCD notebook, where the TFT-LCD luminance was adjustable by the user. The TFT-LCD with a 358 mm diagonal screen provides an active viewing area of 311 mm (horizontal) and 175 mm (vertical). The pixel resolution was 1366 in horizontal and 768 in vertical directions. The screen images were refreshed at a rate of 60 Hz. The maximal contrast ratio and maximal luminance of the TFT-LCD had 10 tunable levels (20–220 cd/m^2) and the subjects were capable of adjusting their favorable luminance. The screen surface was coated with a polarizer to reduce any glare and reflection. According to the guidelines for the text size provided by the ISO standard 9241-303:2011 "Ergonomics of Human-System Interaction—Requirements for Electronic Visual Displays" [20], the distance between the screen and user's eye should be 50~70 cm and the 12 pt text is generally large enough for the text displayed on the screen. As shown in Figure 4, the distant between the screen and the user's eye was 68 cm, and a line of vision was kept at 90° on the VDT screen.

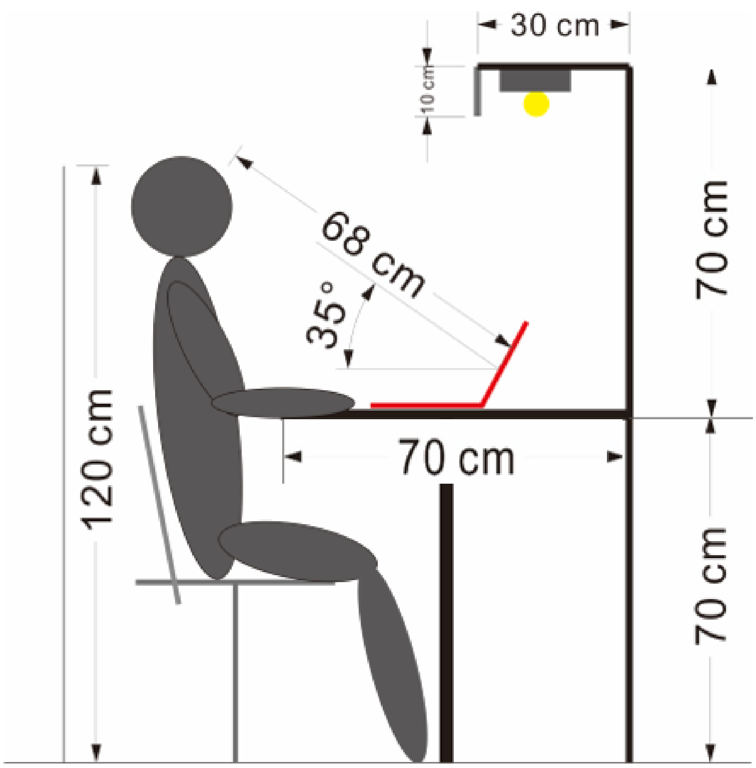
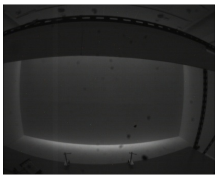
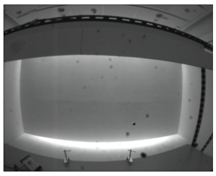
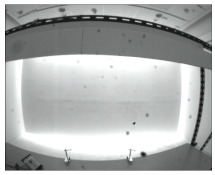


Figure 4. Dimensions of VDT and reading.

2.4.2. Independent Variables

Vertical illuminance is the main factor of ambient lighting in this study. Thus, the ambient lighting illuminance was divided into five different modules according to the vertical illuminance of the subject's human eye position by the illuminance meter as the experimental variable, as illustrated in Table 4. The vertical illuminance was set into 5 lux, 10 lux, 20 lux, 50 lux and 100 lux through adjusting ambient lighting. Under these five independent variables, the horizontal illuminance on the task plane were 6 lux, 10 lux, 13 lux, 43 lux and 79 lux, avg. luminance of space was 2.11 cd/m^2, 3.33 cd/m^2, 4.98 cd/m^2, 14.41 cd/m^2 and 27.36 cd/m^2 and the maximum luminance of space was 21.73 cd/m^2, 27.08 cd/m^2, 33.53 cd/m^2, 76.87 cd/m^2 and 111.91 cd/m^2.

Table 4. Parameters for various illuminance properties.

Factor	1	2	3	4	5
VI	5 lux	10 lux	20 lux	50 lux	100 lux
HI	6 lux	10 lux	13 lux	43 lux	79 lux
Avg. Luminance	2.11 cd/m^2	3.33 cd/m^2	4.98 cd/m^2	14.41 cd/m^2	27.36 cd/m^2
Luminance SD	1.09	1.36	2.62	7.41	15.03
MAX Luminance	21.73 cd/m^2	27.08 cd/m^2	33.53 cd/m^2	76.87 cd/m^2	111.91 cd/m^2
Luminance camera Photo					

VI: Vertical Illuminance. HI: Horizontal Illuminance without desk lighting.

2.5. Experimental Procedure

The experiment was conducted with 20 adults under 40 years old as the participants [21,22]. All subjects had no physiological abnormalities and were in a healthy state with perfect vision. Additionally, the participants had an adequate sleep and were under no medication the day before the test [23]. Each experiment lasted about 60 min. First, the dark adaptation was carried out for about 30 min, and the experimental steps were clearly explained to the subjects at the same time. After the dark adaptation, the questionnaire was answered, and then the task lighting on the desktop was turned on until it met the minimum tolerable minimum illumination of the participants, and then the computer screen brightness was adjusted to the desired value. Upon maintaining the minimum tolerable illuminance for 3 min of VDT operation, the subjects were asked to turn off the lighting on the work surface and turn it back on while adjusting it to their desired illuminance level, and subsequently tune the brightness of the computer screen to a comfortable mode. After maintaining a comfortable and satisfactory working surface illuminance value for 3 min, the working surface illuminance was adjusted to a maximum of 750 lux; followingly, they decreased the working surface illuminance, and reduced the brightness of the computer screen. Each user then followed the following steps: (i) adjusted the illuminance of the working surface from 750 lux down to the minimum tolerated illuminance, (ii) adjusted the computer screen again to a comfortable value, and (iii) terminated the complete set of experiments after three minutes. During the experiment, the experimenter recorded (i) the illuminance of the horizontal working surface, (ii) the vertical illuminance of the human eye position, and (iii) the brightness of the computer screen for each adjustment. The order of the 5 ambient lighting variable experiments was carried out by the Latin Square Design method, as shown in Table 5.

Table 5. Latin square design with five patterns.

1	2	3	4	5	1 = No.1 pattern, 5 lux
2	3	4	5	1	2 = No.2 pattern, 10 lux
5	1	2	3	4	3 = No.3 pattern, 20 lux
3	4	5	1	2	4 = No.4 pattern, 50 lux
4	5	1	2	3	5 = No.5 pattern, 100 lux

2.6. Subjective Psychological Evaluation

In this study, the psychological evaluation of the laboratory lighting environment was collected based on the self-determination theory (SDT) grammar questionnaire. In this protocol, the evaluation contents include the level of the work surface, the brightness, comfort, and satisfaction of the surrounding environment, as well as the work efficiency and recognizability [24–29]. The content of the questionnaire is shown in Table 6. The final assessment of the data was analyzed by the SPSS statistical software for an independent sample (i.e., *t*-test). The significant (*p*) results of *t*-test were highlighted using the following procedure: $p < 0.05$ is marked with *; $p < 0.01$ with **; $p < 0.001$ with ***. This experiment conforms to the public/research ethics and data collection. There was no human invasiveness, and all subjects were informed of their rights and obligations in advance [30].

Table 6. The questionnaire for investigating VDT illuminance strategy with its related factor.

Factors Related to Questions		**Questions and Scales**
Task plane	Brightness	How bright dose the task plane look?
		Very gloomy ①—②—③—④—⑤—⑥—⑦ Very bright
	Comfort	How comfortable is the lighting on task plane?
		very uncomfortable ①—②—③—④—⑤—⑥—⑦ very comfortable
	Satisfaction	How satisfied is the lighting on task plane?
		Very unsatisfied ①—②—③—④—⑤—⑥—⑦ Very satisfied
Ambient space	Brightness	How bright dose the space look?
		Very gloomy ①—②—③—④—⑤—⑥—⑦ Very bright
	Comfortable	How comfortable is the lighting in space?
		very uncomfortable ①—②—③—④—⑤—⑥—⑦ very comfortable
	Satisfaction	How satisfied is the lighting in space?
		Very unsatisfied ①—②—③—④—⑤—⑥—⑦ Very satisfied
Task-Ambient	Satisfaction	How satisfied is the lighting both task lane and space?
		Very unsatisfied ①—②—③—④—⑤—⑥—⑦ Very satisfied
Work performance	Legible	How legible dose article on task plane look?
		Very difficult ①—②—③—④—⑤—⑥—⑦ Very easy
	Productivity	How is your productivity in this space?
		Very bad ①—②—③—④—⑤—⑥—⑦ Very good

3. Results

3.1. Self-Evaluation on Feeling and Work Performance

During the subjective psychological evaluation, the lighting of the work surface was off while turning on the ambient lighting. The average evaluation of 20 subjects shows that as the vertical illuminance of the human eye position increases, the subjects' subjective evaluations, including brightness, satisfaction, predictable work efficiency, and visibility, all increase, as shown in Figure 5.

Analyzing the questionnaire evaluations, the best module is the vertical illuminance of 100 lux, where the horizontal illuminance of the working surface at that time was 79 lux. Thus, this questionnaire shows that although the illuminance of the working surface is far less than the Taiwan CNS standard of 500–750 lux, the users were fairly satisfied with the conditions (i.e., average evaluation) because of the ambient lighting.

In the experiment of adjusting the illuminance of the working surface, four adjustments were made (i.e., adjusting the minimum allowable illuminance value (first two), and the comfort and satisfaction value (latter two times)). There was no difference between the first two times (i.e., *p* value = 0.891), and the subsequent two adjusted illuminance values also remained unaltered (in accordance with the comfortable illuminance by the *t*-test, i.e., *p* value = 0.819). Accordingly, the minimum allowable illuminance value and the comfort satisfaction value were averaged twice, as shown in Figure 6. In the experiment of adjusting the minimum allowable horizontal working surface illuminance, none of the participants turned on the working surface lighting at the 100 lux module, where the 79-lux lighting was able to provide the minimum allowable illuminance for all the participants.

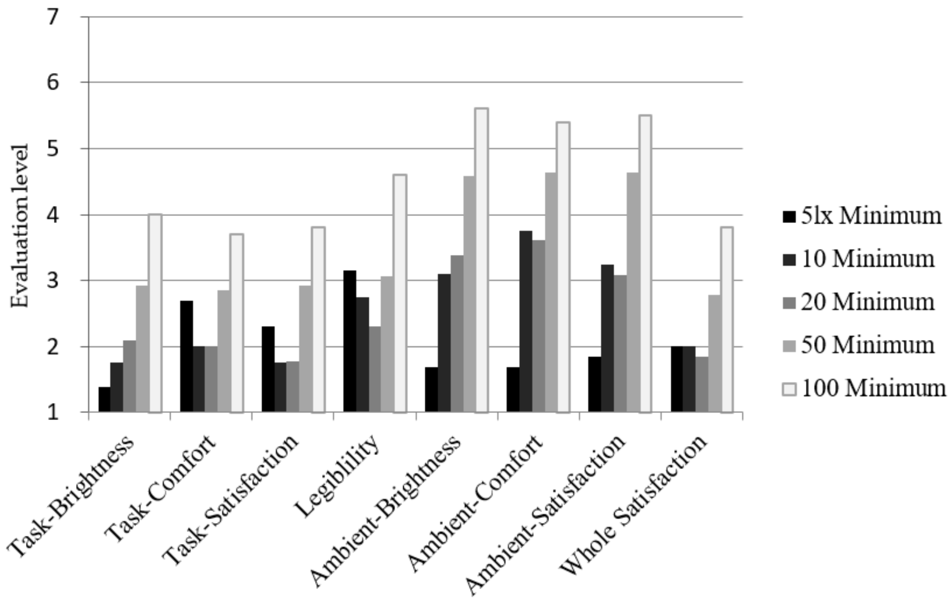


Figure 5. The subjective psychological evaluation. In Y-axis, 1 means negative adjective, such as gloomy, uncomfortable and unsatisfied; 7 means positive adjective, such as bright, comfortable, and satisfied.

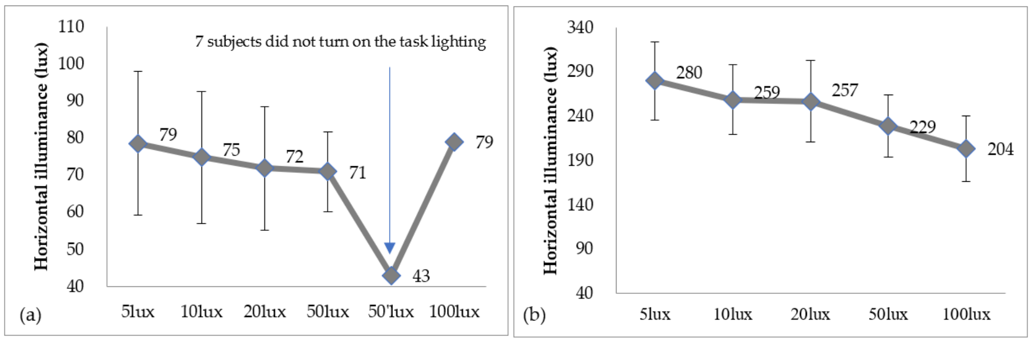


Figure 6. Horizontal illuminance varied with surrounding illuminance: (**a**) minimum horizontal illuminance and (**b**) appropriate horizontal illuminance.

During the 50-lux module experiment, 7 subjects thought that it was unnecessary to turn it on, so that 50 lux lighting was used as an additional record. Meanwhile, the illuminance of the horizontal working surface was set at 43 lux. The average minimum tolerated horizontal illuminance of the 5 modules was 74 lux, which was lower than the current CNS illuminance standard. Considering the average minimum tolerable illuminance of each group, it is found that the minimum tolerable illuminance has a decreasing trend with increased vertical illuminance. When the ambient lighting is relatively bright, the demand for the illuminance on the horizontal working surface can thus be reduced. In a relatively comfortable and satisfactory module, all the subjects turned on the lighting of the work surface and adjusted the illuminance. The average horizontal illuminance of these 5 groups was 246 lux, which was lower than the recommended value of the CNS lighting. A similar observation was confirmed for the minimum allowable illuminance experiment; as the vertical illuminance gradually increased, the operating illuminance on the horizontal plane decreased from 280 to 204 lux.

The illuminance of the horizontal working surface, adjusted by 20 subjects in 5 different vertical illuminance modules, was also systematically analyzed. It was found that the illuminance values adjusted by each user was different; confirming the predictions of the *t*-test (i.e., p value < 0.01 **). As depicted in Figure 7, the regression analysis was carried out on the illuminance adjusted by the participants. When the ambient illumination increased along with the vertical illuminance, the illuminance of the subjects' horizontal working surface was reduced. Accordingly, the results associated with these two illumination modules were consistent.

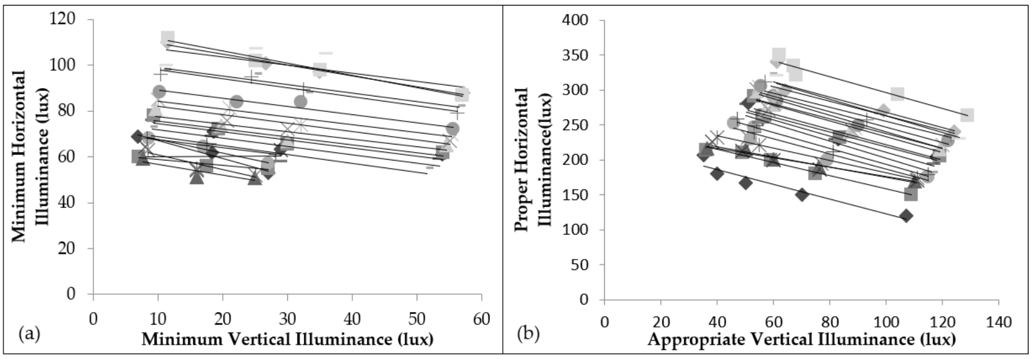


Figure 7. Variation of (**a**) minimum horizontal illuminance and (**b**) proper horizontal illuminance with vertical illuminance. Each line represents the value of adjusted horizontal illumination for each subject.

3.2. VDT Screen Luminance

The computer screen brightness was adjusted after the user determined the minimum allowable and comfortable level of illuminance on the work surface. As depicted in Table 7, the Pearson's correlation coefficient between the vertical illuminance and screen luminance is 0.584. Therefore, it is safe to assume that the computer screen brightness can be determined according to the lighting environment of the work surface, in order to achieve a comfortable screen brightness while the VDT is in operation.

Table 7. Correlation analysis with luminance, vertical illuminance, and horizontal illuminance.

Properties	Luminance	VI	HI
Luminance	1	0.584	0.388
Vertical illuminance		1	0.550
Horizontal illuminance			1

As shown in Figure 8, when the vertical illuminance value of the human eye position increases, the brightness value of the computer screen also increases. To explore the minimum allowable illuminance value, the brightness of the computer screen was increased from 113.8 to 161 cd/m^2; on the other hand, for assessing the comfortable illuminance value, the brightness of the computer screen was increased from 123.3 to 165.5 cd/m^2. As tabulated in Table 5, the computer screen luminance value plays a major role in affecting the vertical illuminance of the human eye, but a minor role in the illuminance of the horizontal working surface. This result can be attributed to the fact that humans' line of sight is to look directly at the computer screen located in front of him/her, which is greatly affected by the ambient lighting. Thus, the computer screen brightness has a high positive correlation with the vertical lighting.

3.3. Relationship between Vertical and Horizontal Illuminance

Our analysis reveals that the vertical lighting severely affects the VDT workers within the office when determining the illuminance value of the horizontal working surface. In other words, the brighter the ambient lighting, the lower the demand for the illuminance of the horizontal working surface. Accordingly, if an appropriate ambient lighting is present, the workers will probably prefer a lower illuminance of the work surface, enabling higher energy saving. As shown in Figure 7, a linear simple regression curve was fitted on the illuminance adjusted by 20 users, where the slope and intercept were statistically analyzed using the Least Squares Method to obtain the mean and standard deviation, as shown in Table A1. All statistical analyses in this study were analyzed with the SPSS software package. The values of slope, constant, and correlation coefficient are presented in Appendix A. The R value is between −0.8 and −1, which indicates that the horizontal illuminance and the vertical illuminance are high and have negative correlations. Only No.4 and No.18 are above −0.8. The R^2 value is higher than 0.8, meaning that more than 80% of the variability of the dependent variable within the data set has been taken into account during the analysis.

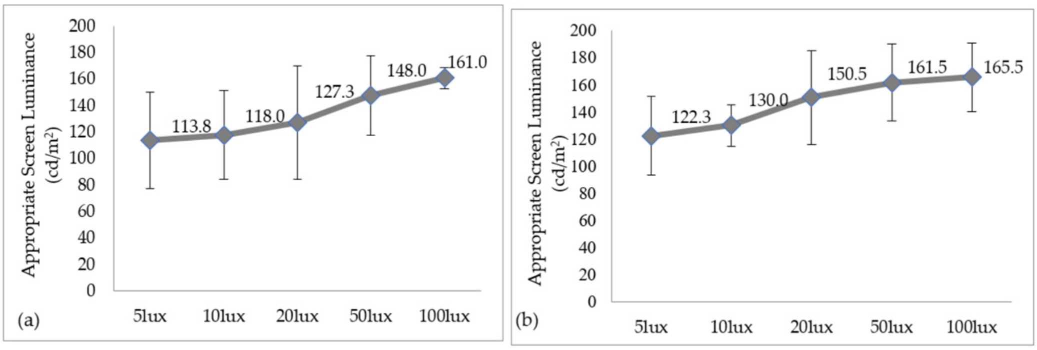


Figure 8. Appropriate screen luminance in different ambient illuminance model: (**a**) minimum model and (**b**) appropriate model.

Herein, two modules were explored: the minimum allowable illuminance and the satisfactory comfortable illuminance. To maximize the energy-saving and to ensure a visible lighting environment, the minimum allowable illuminance was employed, containing the minimum limit value for the participants so that they can perform the general VDT work. Considering the normal distribution, two standard deviations (SDs) covering 95% of the parent range, the following formula can be obtained. Here, the minimum horizontal working surface illuminance (E_{H},min) tolerated by 95% of office workers, varied with vertical luminance (I_{V}), is formulated.

$$E_{\mathrm{H}},\mathrm{min} = -0.41\ I_{\mathrm{V}} + 119 \times (2\ \mathrm{SD}), \tag{1}$$

Indeed, the illuminance of the horizontal working surface, considering the minimum comfort level, is much higher than the minimum allowable illuminance value, leading to the consumption of more energy. Therefore, we consider that the lighting energy saving takes the first priority over meeting the lighting needs of general workers; thus, a formula for assessing the appropriate horizontal Illuminance (E_{H},app), I_{V}, and the average value (Avg) of 50% of the population, can be derived.

$$E_{\mathrm{H}},\mathrm{app} = -1.05\ I_{\mathrm{V}} + 323 \times (\mathrm{Avg}), \tag{2}$$

Considering the power shortage environment and aiming for increased energy saving, linear plots of the illuminance of the horizontal (Task illuminance) work surface versus the vertical illuminance (Ambient illuminance), derived from Formula 1 and Formula 2, were assessed (see Figure 9). As shown in Figure 9, to protect the visual health of the workers, the unacceptable lighting range is demonstrated with the red blocks. The green region is a suitable lighting environment range (i.e., an illuminance range: 95% of the population can tolerate and 50% of the population feels comfortable working in such an environment). The blue regions suggest that 50–95% of the population rated a very comfortable condition, whereas the region above the blue line does not meet the energy-saving requirements.

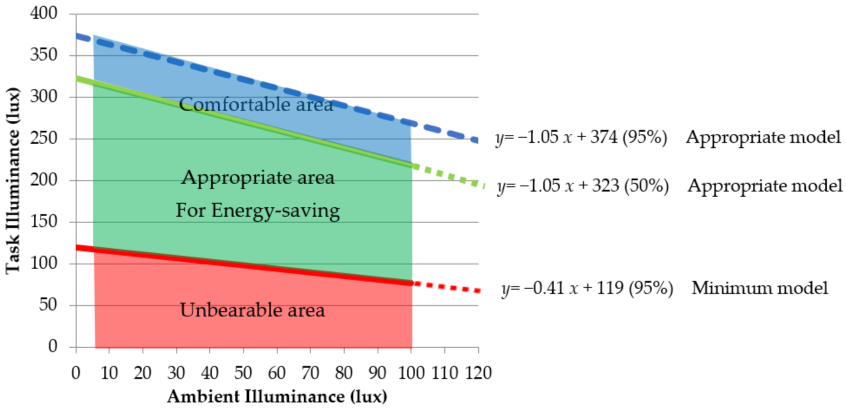


Figure 9. Energy-saving area for task illuminance in different ambient lighting space.

4. Discussion

This study elaborates on an optimal office lighting environment where energy-saving can be maximized. Here, we discussed the following points:

(i) The relationship between the illuminance of the horizontal work surface and the vertical illuminance of the human eye position: The vertical illuminance at the position of the human eye reflects the ambient lighting within the worker's line of sight. When the vertical illuminance at the position of the human eye is low, it means that the ambient lighting is bright enough. When the vertical illuminance of the human eye position is elevated, the illuminance of the worker's horizontal work surface will be adjusted downward. Therefore, there is a negative correlation between these two factors. Indeed, the illuminance of the horizontal working surface of the office alone cannot fully describe the lighting environment of the overall space.

(ii) The range of the minimum allowable horizontal illuminance and satisfactory/comfortable level of illuminance: When considering the energy-saving parameters, the average minimum allowable horizontal illuminance was set to 74 lux, and the average comfortable level illuminance was 246 lux. Both of these values are lower than the current recommended illuminance values for the horizontal working surface of the office, and were adopted in this work to maximize the energy saving. Therefore, it is necessary to consider the regulation of ambient lighting and work surface lighting for the office lighting, while engineering the lighting environment for enhancing the comfort level as well as the energy-saving or shortage of power situation.

(iii) The relationship between the computer screen brightness and office lighting environment: There was a positive correlation between the brightness of the office environment and the computer screen. When the environment is bright, the illuminance of the work surface can be reduced and the brightness of the computer screen needs to be raised. On the contrary, when the environment is dark, the illuminance of the work surface needs to increase and the brightness of the computer screen must be dimmed.

5. Conclusions

In this study, we performed environmental lighting experiments with 20 participants and researched the correlation of desk illuminance, ambient illuminance, and computer screen luminance on the quality of visual comfort. According to our observations and analysis, there is a direct correlation between the ambient lighting (vertical illuminance), work surface lighting (horizontal illuminance), and computer screen brightness. For obtaining a brighter environment, the surface illuminance can be lowered, and the brightness of the computer screen needs to be raised. On the contrary, when the environment is dark, the illuminance of the work surface must increase, whereas the brightness of the computer screen can be reduced.

It is important to note that, in this work, we assumed that the office is under a power shortage situation. Therefore, to save energy, the participants should control their own desk lighting for conducting the VDT work. In a normal condition, the desk horizontal illuminance is usually adjusted at 500 lux, whereas, here, we observed that the participants were satisfied with 246 lux for the desk horizontal illuminance in the power shortage situation. Therefore, with such an adjustment, ~50% more energy can be saved.

This study also has some limitations. We did not elaborate on the visual health of the participants who are in a working environment for an extended period of time with lower than recommended value of the illuminance for that particular working surface. Moreover, we did not study the effect of such lighting conditions on the extended reading on the screen or other prolonged screen-based activities. Here, we only focused on the effect of artificial lighting on the participants' experience with the VDT work. We plan to extend the experimental period, or directly enter the actual office to carry out these targeted and time-dependent experiments. We also plan to analyze the influence of the uniformity of the ambient lighting on the visual comfort. 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, and to provide more detailed suggestions for the lighting control strategies in actual offices.

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

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

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

Appendix A

Table A1. Correlation analysis with luminance, vertical illuminance, and horizontal Illuminance.

Minimum Model					Appropriate Model				
No.	**Slope**	**Constant**	**R**	**R^2**	**No.**	**Slope**	**Constant**	**R**	**R^2**
1	−0.787	75.024	−0.99	0.978	1	−1.0579	228.68	−0.95	0.907
2	−0.252	61.331	−0.95	0.910	2	−0.9278	251.66	−0.99	0.983
3	−0.471	61.47	−0.87	0.760	3	−0.6661	242.67	−0.98	0.969
4	−0.001	60.554	0.00	0.000002	4	−0.7399	248.7	−0.97	0.944
5	−0.656	67.485	−0.95	0.908	5	−0.8925	270.56	−0.98	0.956
6	−0.601	73.714	−0.99	0.972	6	−1.0778	295.17	−0.96	0.925
7	−0.352	71.009	−1	0.9985	7	−1.1233	306.23	−0.99	0.972
8	−0.394	72.891	−0.88	0.770	8	−1.2313	325.04	−0.95	0.902
9	−0.368	75.625	−0.82	0.676	9	−1.1593	326.71	−0.97	0.949
10	−0.355	78.093	−0.91	0.820	10	−1.0507	324.1	−0.97	0.944
11	−0.347	79.145	−0.94	0.884	11	−1.102	331.82	−0.94	0.886
12	−0.333	81.037	−0.89	0.798	12	−1.1373	346.55	−0.96	0.921
13	−0.371	85.793	−0.93	0.870	13	−1.0719	344.66	−0.95	0.899
14	−0.340	87.669	−0.96	0.926	14	−1.1803	357.93	−0.97	0.948
15	−0.355	92.766	−0.97	0.940	15	−1.1154	358.07	−0.97	0.945
16	−0.393	102.02	−0.97	0.938	16	−1.0002	355.41	−0.96	0.914
17	−0.373	102.76	−0.96	0.915	17	−1.0338	366.02	−0.94	0.877
18	−0.355	110.65	−0.69	0.471	18	−1.1811	380.81	−0.98	0.952
19	−0.476	114.47	−0.99	0.989	19	−1.1077	378.58	−0.86	0.744
20	−0.536	116.99	−0.99	0.987	20	−1.1424	410.65	−0.97	0.947
AVG	−0.406	83.523				−1.050	322.501		
SD	0.160	17.700				0.144	51.476		

References

1. Elsaid, A.M.; Ahmed, M.S. Indoor Air Quality Strategies for Air-Conditioning and Ventilation Systems with the Spread of the Global Coronavirus (COVID-19) Epidemic: Improvements and Recommendations. *Environ. Res.* **2021**, *199*, 111314. [CrossRef]
2. Agarwal, N.; Meena, C.S.; Raj, B.P.; Saini, L.; Kumar, A.; Gopalakrishnan, N.; Kumar, A.; Balam, N.B.; Alam, T.; Kapoor, N.R.; et al. Indoor air quality improvement in COVID-19 pandemic: Review. *Sustain. Cities Soc.* **2021**, *70*, 1029423. [CrossRef] [PubMed]
3. Kim, J.; Hong, T.; Lee, M.; Jeong, K. Analyzing the real-time indoor environmental quality factors considering the influence of the building occupants' behaviors and the ventilation. *Build. Environ.* **2019**, *156*, 99–109. [CrossRef]
4. Schiavon, S.; Altomonte, S. Influence of factors unrelated to environmental quality on occupant satisfaction in LEED and non-LEED certified buildings. *Build. Environ.* **2014**, *77*, 148–159. [CrossRef]
5. Elnaklah, R.; Walker, I.; Natarajan, S. Moving to a green building: Indoor environment quality, thermal comfort and health. *Build. Environ.* **2021**, *191*, 107592. [CrossRef]
6. McCunn, L.J.; Kim, A.; Feracor, J. Reflections on a retrofit: Organizational commitment, perceived productivity and controllability in a building lighting project in the United States. *Energy Res. Soc. Sci.* **2018**, *38*, 154–164. [CrossRef]
7. Aslanoğlu, R.; Pracki, P.; Kazak, J.K.; Ulusoy, B.; Yekanialibeiglou, S. Short-term analysis of residential lighting: A pilot study. *Build. Environ.* **2021**, *196*, 107781. [CrossRef]
8. Gerhardsson, K.M.; Laike, T. User acceptance of a personalised home lighting system based on wearable technology. *Appl. Ergon.* **2021**, *96*, 102941. [CrossRef]
9. Mathew, P.; Regnier, C.; Shackelford, J. Energy Efficiency Package for Tenant Fit-Out: Laboratory Testing and Validation of Energy Savings and Indoor Environmental Quality. *Energies* **2020**, *13*, 5311. [CrossRef]
10. Taiwan Economic Ministry. *CNS 12112 Lighting of Indoor Work Places*; Standard Inspection Bureau of the Ministry of Economic Affairs: Taipei, Taiwan, 2012.
11. International Commission on Illumination. *CIE S 008/E-2001 Lighting of Indoor Work Places*; International Commission on Illumination: Vienna, Austria, 2002.
12. Parihar, J.; Jain, V.K.; Chaturvedi, P.; Kaushik, J.; Jain, G.; Parihar, A.K. Computer and visual display terminals (VDT) vision syndrome (CVDTS). *Med. J. Armed Forces India* **2016**, *72*, 270–276. [CrossRef]
13. Toomingas, A.; Hagberg, M.; Heiden, M.; Richter, H.; Westergren, K.E.; Tornqvist, E.W. Risk factors, incidence and persistence of symptoms from the eyes among professional computer users. *Work* **2014**, *47*, 291–301. [CrossRef] [PubMed]
14. Montani, G.; Treso, F.; Martena, M. Effects of different contact lens design on accommodative function and eyestrain symptoms of young adult subjects after VDT use. *Contactlens Anterior Eye* **2022**, *45*, 101642. [CrossRef]
15. Liu, K.; Chiang, C.; Lin, Y. Influences of visual fatigue on the productivity of subjects using visual display terminals in a light-emitting diode lighting environment. *Archit. Sci. Rev.* **2010**, *53*, 384–395. [CrossRef]
16. Yoshizawa, N.; Mochizuki, E.; Iwata, T. Actual conditions of illuminance/luminance/luminance distribution and workers' evaluation under setsuden. *AIJ* **2019**, *84*, 385–395. [CrossRef]
17. Mochizuki, E.; Yoshizawa, N.; Iwata, T.; Munakata, J.; Hirate, K.; Akashi, Y. The impact on power-saving measures on office lighting in 2011. *AIJ* **2013**, *78*, 9–16. [CrossRef]
18. Lin, Y.; Koga, T.; Hirate, K.; Kuo, Y. The Field Office Survey for Lighting Environment in Taiwan. *Appl. Mech. Mater.* **2014**, *496*, 2569–2574. [CrossRef]
19. Lin, Y. A Study on Brightness and Allowable Illuminance in Working Space. Ph.D. Thesis, The University of Tokyo, Tokyo, Japan, 2014.
20. *ISO 9241-303:2011*; Ergonomics of Human-System Interaction—Part 303: Requirements for Electronic Visual Displays. International Organization for Standardization: Geneva, Switzerland, 2011.
21. Sullivan, L.M.; Weinberg, J.; Keaney, J.F. Common statistical pitfalls in basic science research. *J. Am. Heart Assoc.* **2016**, *5*, e004142. [CrossRef]
22. Ma, J.H.; Lee, J.K.; Cha, S.H. Effects of lighting CCT and illuminance on visual perception and task performance in immersive virtual environments. *Build. Environ.* **2022**, *209*, 108678. [CrossRef]
23. 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. [CrossRef]
24. Papinutto, M.; Nembrini, J.; Lalanne, D. "Working in the dark?" investigation of physiological and psychological indices and prediction of back-lit screen users' reactions to light dimming. *Build. Environ.* **2020**, *186*, 107356. [CrossRef]
25. Dangol, R.; Islam, M.S.; Hyvärinen, M.; Bhushal, P.; Puolakka, M.; Halonen, L. User acceptance studies for LED office lighting: Preference, naturalness and colourfulness. *Light. Res. Technol.* **2015**, *47*, 36–53. [CrossRef]
26. De Bakker, C.; Aarts, M.; Kort, H.; Rosemann, A. The feasibility of highly granular lighting control in open-plan offices: Exploring the comfort and energy saving potential. *Build. Environ.* **2018**, *142*, 427–438. [CrossRef]
27. Kim, M.K.; Müller, H.M.; Weiss, S. What you "mean" is not what I "mean": Categorization of verbs by Germans and Koreans using the semantic differential. *Lingua* **2021**, *252*, 103012. [CrossRef]
28. Li, Z.; Sun, X.; Zhao, S.; Zuo, H. Integrating eye-movement analysis and the semantic differential method to analyze the visual effect of a traditional commercial block in Hefei, China. *Front. Archit. Res.* **2021**, *10*, 317–331. [CrossRef]

29. Heo, L.; Kozaki, M.; Koga, T.; Hirate, K.; Kim, H. Investigation of the Visual Environment of Railway Station Stairs Using Qualitative and Quantitative Evaluation Methods. *Energies* **2022**, *15*, 7013. [CrossRef]
30. Luk, H.N.; Ennever, J.F.; Day, Y.J.; Wong, C.S.; Sun, W.Z. Tiny tweaks, big changes: An alternative strategy to empower ethical culture of human research in anesthesia (A Taiwan Acta Anesthesiologica Taiwanica-Ethics Review Task Force Report). *Acta Anaesthesiol. Taiwanica* **2015**, *53*, 29–40. [CrossRef]