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A Field Study of Individual, Energy-Efficient, and Human-Centered Indoor Electric Lighting: Its Impact on Comfort and Visual Performance in an Open-Plan Office Part 1

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Abstract: In this field study, we examined the impact of human-centered lighting on an open-plan office environment, involving the participation of sixty office workers. The objective was to investigate the effects of the Circadian Stimulus (CS) and Equivalent Melanopic Lux (EML) metrics. This study took place at Istanbul Technical University in Istanbul, Turkey. The office was equipped with single Correlated Color Temperature (CCT) light emitting diode (LED) sources, featuring two different light beam distributions: Direct Suspended Linear (L_1) and Direct and Indirect Suspended Linear (L_2). To minimize energy consumption, we proposed simulations for a suspended individual lighting system. The office workers were invited to complete visual cognitive performance tests, proofreading tasks, and the Karolinska Sleepiness Scale (KSS) test to measure alertness. Additionally, participants were asked to provide feedback on the comfort criteria associated with the designed human-centered lighting concept. The preliminary findings from part 1 of this field study shed light on the potential of office lighting modifications in enhancing energy efficiency and meeting the standards set by WELL v2 2023 Q4 and UL Design Guideline 24480 (2019). Part 2 of this study will further optimize the proposed lighting quality concept to determine the most suitable individual lighting solution for office workers.

Keywords: human-centric lighting; equivalent melanopic lux; circadian stimulus; energy efficiency; office lighting

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1. Introduction

Human-centric lighting (HCL) has gained significant attention in recent years as an innovative approach to lighting design in buildings. For over two decades, researchers have been investigating the impact of light on health in offices. However, recent technological advancements and a deeper understanding of physiological responses have prompted researchers to reconsider their approach to studying the influence of light in real-life settings. The objective of this study is to observe how occupants in an actual office setting respond to human-centered lighting while considering its effects on comfort criteria. Circadian effectiveness is often used as a synonym for the potency of light in eliciting positive, non-visual responses in humans. These responses encompass circadian [1,2], neuroendocrine [3,4], and neurobehavioral [5–7] reactions mediated by signals from retinal photoreceptors, including rods, cones, and intrinsically photosensitive retinal ganglion cells (ipRGCs). One of the goals is to develop indoor lighting solutions that dynamically adapt to the physiological and biological needs of occupants to support positive human outcomes, such as improved sleep, health, and well-being [8], while also considering traditional vision-related aspects of lighting quality [9].

Unlike traditional lighting systems that focus solely on visual acuity, HCL aims to enhance human well-being and performance by considering the non-visual effects of light on individuals. This emerging field recognizes that light has a profound impact on human physiology, cognition, and emotional states [10]. Research studies have shown the potential benefits of HCL in various building types, including offices, healthcare facilities, educational institutions, and residential spaces. For instance, studies have demonstrated that properly designed HCL systems can improve employee productivity and satisfaction in office environments, enhance patient outcomes in healthcare settings, and support student performance and well-being in educational facilities [11].

To implement HCL effectively, lighting designers need to consider factors such as the timing, intensity, and spectral characteristics of light. This requires a holistic approach that integrates architectural design, lighting control systems, and occupant preferences and needs. While HCL holds great promise for improving the quality of lighting in buildings, challenges remain in terms of standardization, cost-effectiveness, and occupant acceptance. However, ongoing research and advancements in lighting technology are driving the adoption of HCL in the design and operation of buildings. When designing lighting solutions for the built environment, practitioners typically need to consider lighting parameters falling into one of the four categories listed in [12,13]. For this purpose, the Circadian Stimulus (CS) metric, a physiologically relevant measure of circadian effectiveness in lighting, and the Equivalent Melanopic Lux (EML), referred to as CIE S 026:2018 [14], are commonly used metrics for assessing circadian lighting effects, measured in m-lux and lux, respectively. These metrics involve applying specific response functions to the light spectrum and incorporating light intensity as a scaling factor. Both EML and M-EDI metrics stand for melanopic effective dose of illuminance. These are metrics used to quantify how light affects the body's circadian system, considering the intensity and spectral composition of light that stimulates melanopsin receptors in the eyes, which play a role in regulating sleep–wake cycles. They are totally based on the melanopic response of intrinsically photosensitive retinal ganglion cells, as elucidated in the work of Lucas et al. [15]. These cells exhibit their highest sensitivity at 480 nm. The primary difference lies in the reference sources employed, equal energy for EML and D65 for M-EDI. The two metrics can be converted by using a simple scalar multiplier (EML $\approx$ M-EDI $\times$ 1.103).

The CS metric assesses the effectiveness of light in suppressing melatonin through a more complex model of human phototransduction. This model integrates data from experiments on human nocturnal melatonin suppression and takes into account estimations of rod and cone photoreceptor responses. Notably, the most recent update to this model occurred in 2021 [16,17].

Office workers spend the majority of their time indoors, highlighting the importance of maintaining a healthy office environment. Lighting plays a crucial role, but there is limited knowledge about its effects in practical work settings. Alertness was found to be significant in four out of five studies that utilized the Karolinska Sleepiness Scale (KSS) [18]. This scale indicates the level that best reflects the subject's psychophysical state experienced in the previous 10 min [19]. The Stanford Sleepiness Scale (SSS) was also used to examine lighting conditions and other factors [20]. In addition to alertness and sleep-related effects, it is essential to understand how occupants evaluate and feel satisfied with different lighting conditions. Understanding occupant satisfaction and appraisal of various lighting conditions is important, in addition to their effects on alertness and sleep. A study found that participants reported significantly higher daytime sleepiness when exposed to high illuminance levels in the morning compared to low morning light exposure, and visual effects were more significant than non-visual effects, highlighting their importance in lighting considerations [21]. However, there is limited research on lighting's non-visual effects in real office environments. The authors of [22] address that gap by demonstrating that properly applied light can promote circadian entrainment and increase alertness. Regarding [23], the lighting conditions in home office settings during the COVID-19 pandemic were analyzed, alongside an investigation into the desire for HCL installations. Most participants expressed a preference for HCL for office tasks, emphasizing the importance of factors such as well-being, efficiency, and cost-effectiveness in their lighting choices. Therefore, this study aims to provide the optimal scenario for office workers based on their comfort preferences. The office environment was simulated across six different cases, and the simulation results are detailed in the simulation section. Similar conditions were applied in each case. In the experimental design section, measurements for the open-plan office are listed. The concept involves occupants participating in visual tests and surveys prepared for each scenario. Finally, this paper presents the statistical results regarding participants' preferences and performances.

2. Study Design

Two organizations, Underwriters Laboratories (UL) [24] and the International WELL Building Institute (IWBI), have established guidelines for incorporating the human circadian system into office lighting design. Under UL Design Guideline 24480 (UL 2019) [24], guidelines are provided for creating and verifying effective circadian lighting in offices, primarily using the CS metric. In addition to these circadian metrics, the lighting design takes into account the Illuminating Engineering Society (IES) guidelines for color rendering and task illumination, including uniformity ratios. This study sets goals for both simulation design and experimental design. The WELL framework encompasses various environmental aspects and allows for earning certification points through design features, including the circadian lighting feature, which is a feature that aims to provide varying levels of EML [25].

This study consisted of a simulation phase and a series of consecutive experiments conducted in an open-plan office. The main objective of these experiments was to investigate how different lighting conditions impact the overall experiences of office occupants. The CS metric, a physiologically relevant measure of circadian effectiveness in lighting outlined in UL 24480 [24], and the EML metric, referred to in CIE S 026:2018 [14], served as the corresponding evaluation schemes for the proposed human-centered lighting design. The targets for the study regarding UL 24480 and WELL v2 2023 Q4, which is based on CIE S 026:2018, are presented as the recommended metric thresholds in Section 2.1.

The selected office has dimensions of 4.9 × 4.6 × 2.8 m and is located in the Energy Institute of Istanbul Technical University on the Ayazaga Campus, Maslak, Istanbul, Turkey, with a geographic location of 41°06′27.7″ N 29°01′50.9″ E. The lighting target was set at a working plane height of 0.8 m from the floor. The reflectance values for the office were measured as follows with a luminance meter: 40% for the floor, 90% for the walls, 90% for the ceiling, 2.5% for chairs, and 86% for desks and drawers [26]. These values were used as inputs for simulation studies as well. Figure 1 shows a diagram of the study procedure. By conducting simulations, valuable insights were gained that informed the next steps of the project. The simulations helped in understanding the impact of varying mounting heights on the requested standards and provided a basis for experimental testing. In the results section of this research of the approach, it was observed that by adjusting the height of the luminaires to an optimal level, the required illuminance levels for both energy saving and the optimal suspended height of light were achieved. This allowed for the implementation of dimming strategies to conserve energy without compromising lighting quality. To enhance the understanding of this study's outline, a schematic diagram is provided in Figure 1.

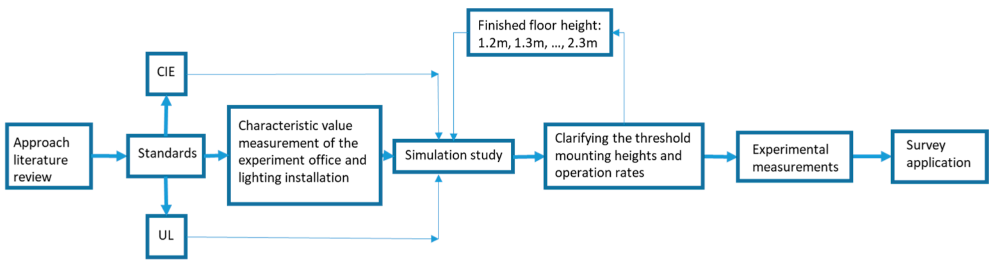


Figure 1. Diagram of study procedure.

The simulation study for the open plan was completed, with experimental measurements conducted to verify the simulated results in the experimental phase. The aim is to confirm the statistical validity of the proposed cases through analysis.

2.1. Circadian Lighting Metrics

According to the standards, office workers are required to maintain a minimum CS of 0.3 during office hours and 0.4 during the highest productivity time zone. The study aims to achieve a CS of 0.3 in all scenarios. Additionally, the EML needs to surpass 275 to achieve a higher rank on the WELL v2 2023 Q4 target, earning three points toward WELL certification. To calculate the CS, the Spectral Power Density (SPD) of luminaires must be entered into the online calculator provided by the Lighting Research Center (LRC) [16,27]. This calculation is based on the vertical illuminance (E_V) of the occupant's line of sight in the office. Similarly, to determine the EML, the same SPDs are input into the Melanopic Ratio (MR) calculator [28] to obtain the MR value for each individual luminaire.

The SPDs of the luminaires were measured experimentally at the photometry and radiometry laboratory of the Energy Institute at Istanbul Technical University, covering wavelengths from 380 nm to 730 nm. The MR values calculated by the MR calculator indicate an MR of 0.722 for L_2 lighting and 0.651 for L_1 lighting system. The evaluation of the desk's Horizontal Illuminance (E_H) and the direction of E_V at the occupant's eye level was performed at three different height steps: H_1 at 1.5 m, H_2 at 1.8 m, and H_3 at 2.3 m above the finished floor. The distance from the wall behind the occupant was set at 1.2 m. These measurements were taken to achieve the target CS and EML levels, as shown in Table 1.

Table 1. Targets for EML and CS regarding documentation.

Documents	Recommendations
WELL v2 2023 Q4	EML $\geq$ 275 [250 M-EDI]
UL Design Guideline 24480 (2019)	CS $\geq$ 0.3

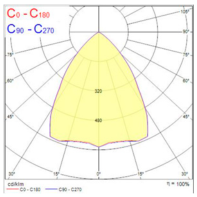
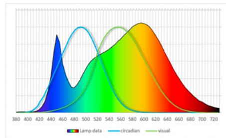
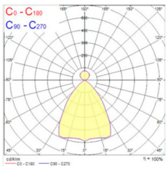
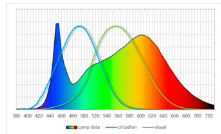
Regarding WELL Standard—v3 2020, light models or light calculations with at least 250 EML are required at 75% or more of workstations, measured on the vertical plane facing forward, 1.2 m above the finished floor in view of the occupant [29].

2.2. Simulation Design

The design of luminaires for office lighting should prioritize meeting the requirements of workers, as the type of luminaire chosen plays a crucial role in defining the ambiance and lighting levels in the workspace. The most energy-efficient solution that aligns with occupant-centered lighting on an individual level is considered the best fit. In our research, we selected two luminaire types, namely Direct Suspended Linear (L_1) and Direct and Indirect Suspended Linear (L_2) with an 80% downlight and 20% uplight ratio, which were deemed the best fit based on their high output outcomes in terms of CS and EML, as reported in [30–32]. Details of the specifications are listed in Table 2.

A simulation methodology was implemented for both L_1 and L_2 luminaires with a Correlated Color Temperature (CCT) of 3800 K to meet the illuminance level requirements of the office workers on both the vertical and horizontal planes. The E_V and dynamic luminaire mounting height were evaluated accordingly. The simulation was conducted using DIALux Evo 10 [33] and Microsoft Excel 2016 for the open-plan office.

Table 2. L_1 and L_2 luminaire specifications.

Luminaire Name	Luminaire Photo	Photometry	Total Power Consumption (W)	Luminous Flux (Lumen)	Correlated Color Temperature (K)	Melanopic Sensitivity Curve	MR
L_1			27	2947	3800		0.651
L_2			34	3315	3800		0.722

The illuminance levels were calculated using a horizontal calculation surface with desk dimensions of 0.8 × 1.3 m, set at a height of 0.8 m above the finished floor level. Additionally, calculations of E_V were proposed at a height of 1.2 m above the finished floor, aligned with the human eye level and direction of view. In Figure 2, picture A depicts a simulated open-plan office with two viewing directions, while picture B illustrates the participants' viewing direction at eye level (H: 1.2 m). The mounting heights of L_1 and L_2 at H_1, H_2, and H_3 are presented in Figure 2, B accordingly. The E_H at the desk and E_V at the occupant's eye level were evaluated at three different heights: H_1 at 1.5 m, H_2 at 1.8 m, and H_3 at 2.3 m above the finished floor, with a 1.2 m distance from the wall behind the occupant.

(**A**) (**B**)

Figure 2. (**A**): simulated open-plan office. (**B**): participant's view direction height at H: 1.2 m and L_1 and L_2 mounting heights at H_1, H_2, H_3.

We evaluated the required E_V and dynamic luminaire mounting height to determine the Optimum Luminaire Height (OLH). Based on the evaluation results, the OLH for both L_1 and L_2 is determined to be H_2 at 1.8 m above the finished floor. This allowed us to obtain CS of 0.3 and EML above 275 on the H_2 with dimming rate of 40% that applied on luminaires, in order to gain not only meet the minimum target amounts but also energy saving with the OLH. Derived from the simulation outcomes, two threshold heights, CS 0.3 and 0.4 for OLH, were established for the lighting luminaires. The simulation results demonstrate that at the OLH, CS exceeds 0.4, which surpasses the target of our approach. Hence, 40% dimming was implemented in the H_2 scenario to maintain CS at 0.3, the same as the H_1 and H_3 scenarios, as shown in Table 3.

Table 3. The results of the simulation of the office for L_1 and L_2.

	L_1				L_2		
	H_1	H_2	H_3		H_1	H_2	H_3
Height (m)	1.5	1.8	2.3	Height (m)	1.5	1.8	2.3
E_V 1.2 m (lux)	532	873	561	E_V 1.2 m (lux)	437	678	432
E_V 1.2 m dimmed (lux)	-	525	-	E_V 1.2 m dimmed (lux)	-	387	-
CS	0.303	0.404	0.314	CS	0.329	0.416	0.326
CS dimmed	-	0.3	-	CS dimmed	-	0.3	-
EML (m-lux)	346	568	365	EML (m-lux)	316	490	312
Mel-EDI (m-lux)	314	515	331	Mel-EDI (m-lux)	286	444	283
EML dimmed (m-lux)	-	342	-	EML dimmed (m-lux)	-	279	-
Mel-EDI dimmed (m-lux)	-	310	-	Mel-EDI dimmed (m-lux)	-	253	-
MR	0.651	0.651	0.651	MR	0.722	0.722	0.722
E_H Desk (lux)	1505	1011	580	E_H Desk (lux)	1100	763	460
U_0 Desk	0.44	0.63	0.8	U_0 Desk	0.47	0.67	0.83
E_H Desk Dimmed (lux)	-	607	-	E_H Desk Dimmed (lux)	-	445	-
U_0 Desk Dimmed	-	0.64	-	U_0 Desk Dimmed	-	0.67	-

2.3. Experimental Study

As mentioned before, the reflectance values in the office were measured as follows: 40% for the floor, 90% for the walls, and 90% for the ceiling. The chairs had a reflectance value of 2.5%, while the desks and drawers had a reflectance value of 86%. Based on the simulation results, two threshold values and one OLH were defined for the lighting luminaires. Threshold heights were selected based on the minimum CS 0.3 target so the minimum height was 1.5 m and the maximum was 2.3 m above the finished floor. The luminaire mounting system was intentionally engineered to be adjustable, allowing for dynamic positioning during experimental trials for each participant. As part of the testing process, the luminaire was carefully positioned at H_1, H_2, or H_3 as required. These scenarios, derived from the simulation results, were then implemented in the sample office. During office hours, participants completed surveys and tests to gather subjective feedback on various aspects, including comfort criteria, workplace satisfaction, lighting quality, environmental satisfaction, alertness, mood, and motivation. Figure 3 illustrates the layout of the study office, which intentionally lacks access to daylight.

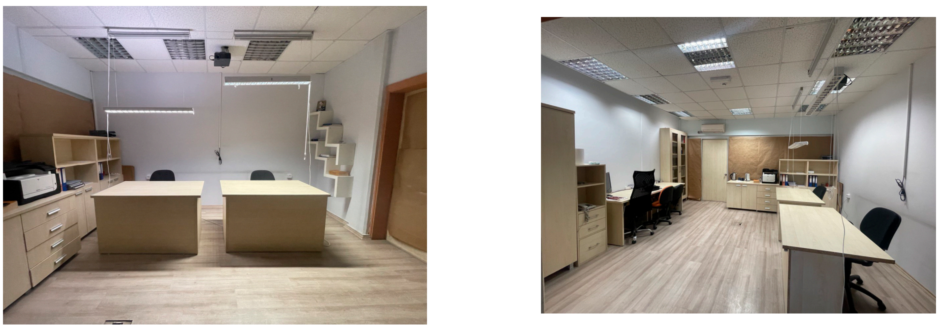


Figure 3. Photos of experimental open-plan office.

Table 4 provides information about the open-plan office. It is important to note that all windows in the office were covered to eliminate the influence of natural daylight, creating a controlled environment solely influenced by the experimental artificial lighting conditions.

Table 4. The results of the measurement of the open-plan office for L_1 and L_2.

	L_1				L_2		
	H_1	H_2	H_3		H_1	H_2	H_3
Height (m)	1.5	1.8	2.3	Height (m)	1.5	1.8	2.3
E_V 1.2 m (lux)	523	853	550	E_V 1.2 m (lux)	420	630	400
E_V 1.2 m dimmed (lux)	-	520	-	E_V 1.2 m dimmed (lux)	-	393	-
CS	0.3	0.404	0.31	CS	0.321	0.402	0.311
CS dimmed	-	0.3	-	CS dimmed	-	0.3	-
EML (m-lux)	340	555	358	EML (m-lux)	303	455	289
Mel-EDI (m-lux)	309	503	325	Mel-EDI (m-lux)	275	412	262
EML dimmed (m-lux)	-	338	-	EML dimmed (m-lux)	-	284	-
Mel-EDI dimmed (m-lux)	-	307	-	Mel-EDI dimmed (m-lux)	-	257	-
MR	0.651	0.651	0.651	MR	0.722	0.722	0.722
E_H Desk (lux)	2026	1200	753	E_H Desk (lux)	1138	760	522
U_0 Desk	0.87	0.88	0.90	U_0 Desk	0.97	0.96	0.94
E_H Desk Dimmed (lux)	-	870	-	E_H Desk Dimmed (lux)	-	520	-
U_0 Desk Dimmed		0.94		U_0 Desk Dimmed		0.92	

The similarity between the simulation and experimental results indicates the accuracy of the simulation model. Factors such as the model's fidelity, the accuracy of the input parameters, and the quality of the experimental data influence this similarity. When simulation results closely match experimental observations, it provides confidence in the model's predictive capabilities and its ability to represent real behavior.

2.4. Surveys

This research was conducted between March 2023 and July 2023, involving 60 participants with an average experimental period of 100 min. This study aimed to compare office lighting with dynamic height and gathered subjective feedback through surveys and tests within specified timeframes. The collected feedback encompassed comfort criteria, workplace satisfaction, lighting quality, environmental satisfaction, alertness, mood, and motivation. The research took place in an open-plan office space located at Istanbul Technical University.

The primary objective of this study was to investigate how different lighting conditions influenced individuals' experiences. Three trials were conducted within the office space, with each experiment consisting of three distinct sessions. In Session 1, participants performed cognitive tasks to assess their performance under different lighting conditions. Session 2 focused on evaluating participants' visual perception using Questionnaire 1 (Q1, Appendix B, Figure A2), a cognitive performance test, and Questionnaire 2 (Q2, Appendix B, Figure A3), a proofreading task, under lighting in H_1, H_2, and H_3 conditions. Session 3 aimed to gather valuable participant feedback regarding their experiences with the specific lighting systems used in the experiments.

To ensure a representative sample, the participants were carefully balanced, with 31 Male and 29 Female participants, divided into three age groups: 20–30, 30–40, and above 40. This study employed a unique approach due to the office layout and limited desk availability.

This comprehensive study aimed to thoroughly investigate the impact of lighting conditions on occupants' cognitive performance, visual perception, and subjective experiences within an office setting. The deliberate variations in luminaire heights and the consideration of participant demographics contribute to the robustness of this study's findings. At the beginning of this study, demographic information about the participants was collected (See Appendix A, Figure A1), including age, gender, eye disorders, and whether they wore eyeglasses or contacts while working. The results regarding this information are presented in Figure 4.

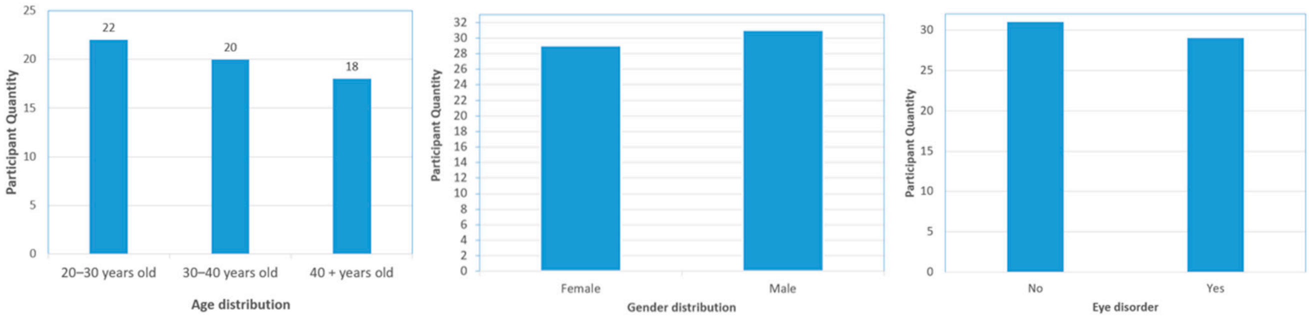


Figure 4. Demographic information about the participants.

It is worth noting that the participants' workstations were located in an open office area with suspended lighting. The objective of this study was to develop a research methodology that improves the current understanding of how lighting affects the physiological and psychological responses of individuals in an office environment. To ensure clarity for the participants and facilitate statistical analysis, most of the questions were presented in a five-point Likert scale format. Figure 5 illustrates the experimental procedure that was followed for each participant. The feedback loop for each participant was reiterated for scenarios L_1H_1, L_1H_2, L_3H_3, as well as L_2H_1, L_2H_2, and L_2H_3. Time-related details, such as the timing of answering the experiments and errors quantity, were provided as input data for statistics.

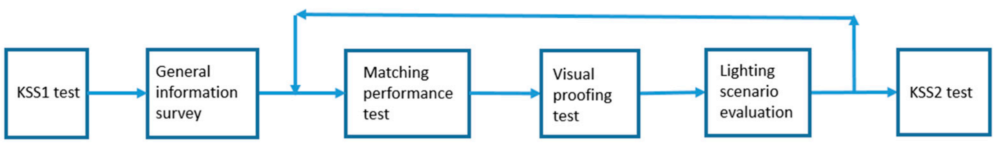


Figure 5. Experimental procedure that followed for each participant.

3. Results

Following the simulation phase of this study, the experimental setup was finalized, and participants were engaged for the purpose of analyzing their feedback concerning the various lighting scenarios. Changes in lighting levels, psychological comfort, and performance were scrutinized in alignment with H_1, H_2, and H_3 pertaining to lighting conditions L_1 and L_2. In order to evaluate the influence of lighting level adjustments on psychological comfort, participants underwent a series of inquiries and visual assessments (Q1, Q2) across six distinct lighting scenarios within the office setting. This study employed an experimental framework deemed "appropriate" for investigating lighting conditions that are human-centric, in addition to those addressing physiological comfort parameters. Both Q1 and Q2 were administered to every participant during the survey process, with error quantification and time expended serving as metric scales. Furthermore, the preferences of occupants were gauged based on their comfort-related criteria.

The information of mean serves as the average of the sample data and represents the central value in statistics. Hence, questionnaires based on opinions were developed to evaluate the comfort criteria of the occupants. The participants' levels of sleepiness were measured using the KSS, which was administered both at the beginning and end of the survey (see Appendix A, Figure A1 and Appendix D, Figure A5). At the beginning of each set of luminaires, participants were asked about their satisfaction with their workplace, specifically with their workstations. Subjective feedback regarding the comfort of office furnishings and the adequacy of the available space for individual work was also collected at Figure 6.

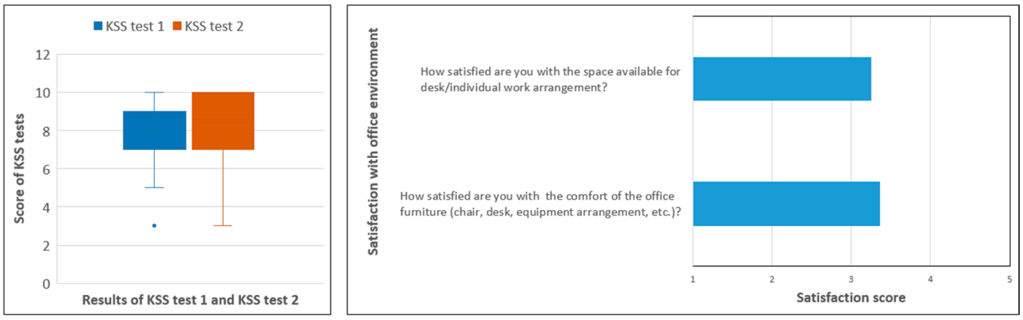


Figure 6. (**Left**): KSS 1 and KSS 2 answers; (**Right**): satisfaction with office environment.

Furthermore, the effect on participants was assessed using the short form of the Positive and Negative Affect Schedule (PANAS) [34]. The 10 items of the PANAS short form were presented in a random order. Additionally, three additional questions were included to measure participants' current mood, physical well-being, and motivation to complete their ongoing tasks [35]. The PANAS survey was provided at the beginning of the tests, and the results are shown in Figure 7.

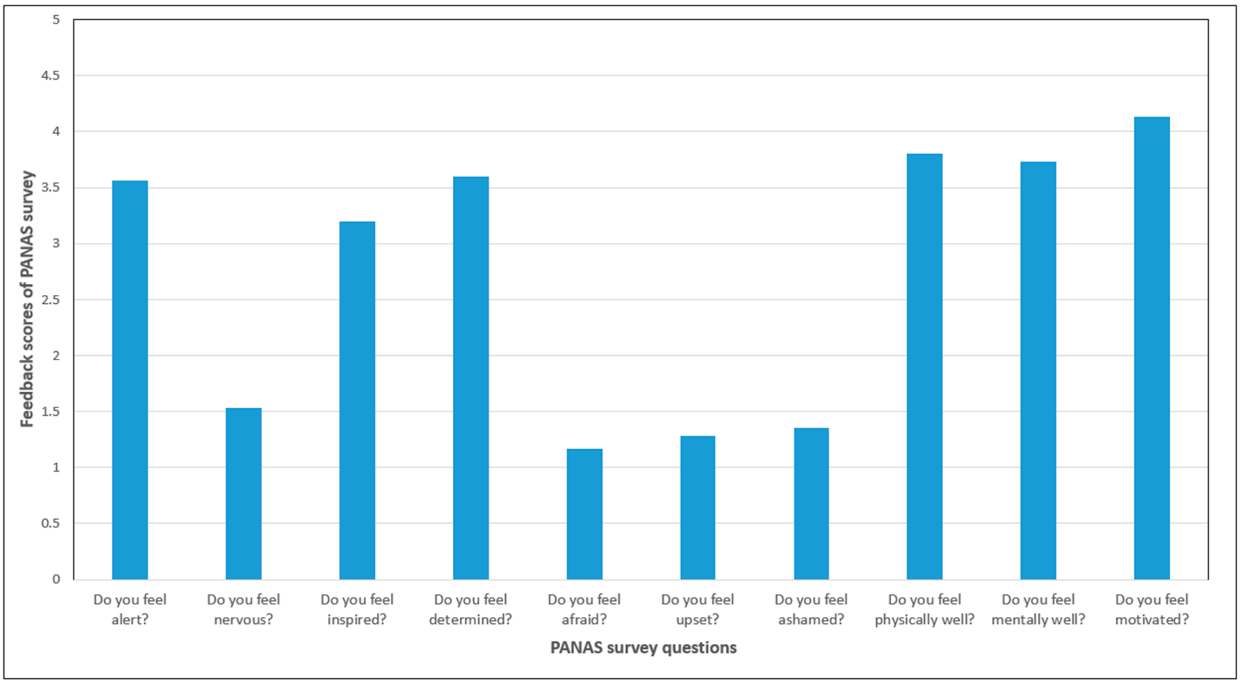


Figure 7. PANAS survey questions and feedback from 60 participants.

The lighting satisfaction survey was conducted at the conclusion of each set of luminaires. Participants were asked to indicate their level of satisfaction by responding to the following statements: "I am satisfied with the lighting", "There is an appropriate level of illumination for the task I am currently performing", "The color of the light is pleasant", "The lighting is unified on the desk", and "The height of lighting is pleasant". Additionally, they were requested to rate the lighting on a scale ranging from Uncomfortable to Comfortable, Not Uniform to Uniform, and Unsuitable to Suitable, taking into consideration the luminaire height. Figure 8 presents the comparative satisfaction results among H_1, H_2, and H_3 for L_1 and L_2 (see Appendix C, Figure A4).

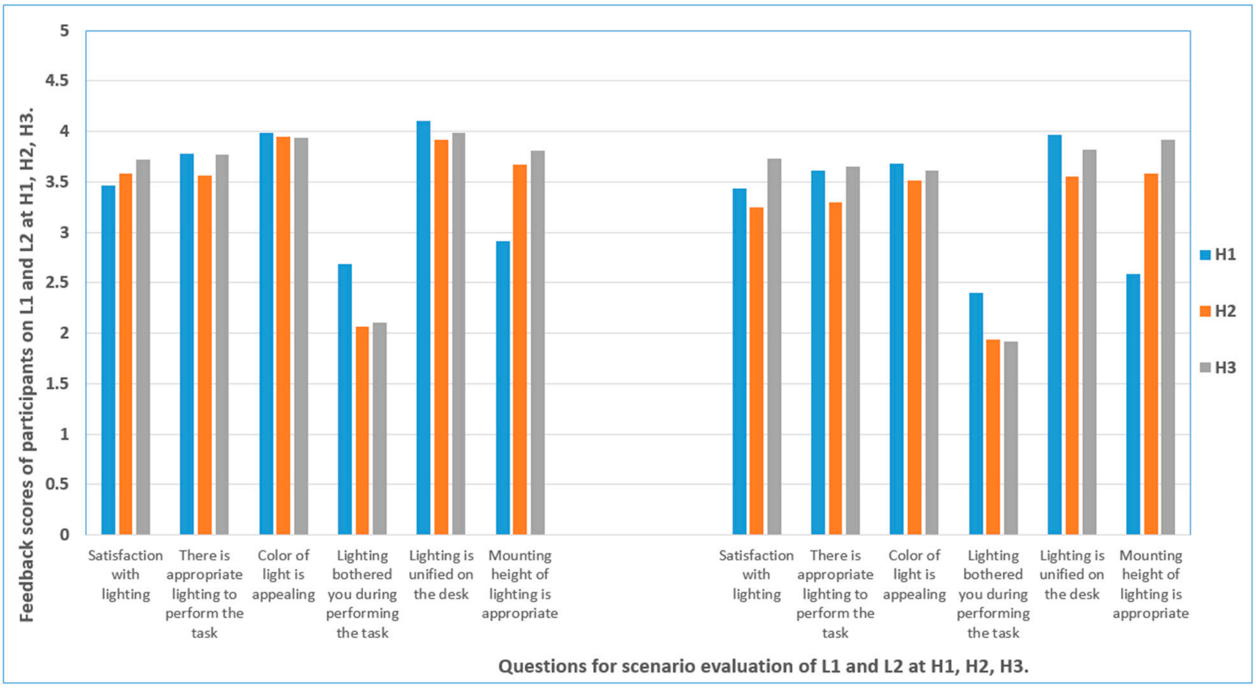


Figure 8. The pleasure rating reviews of participants at H_1, H_2, H_3.

The EML and CS values were calculated for each desk based on the calculated and measured eye-level illuminances and SPDs. All the collected data were used to compare the evaluation differences between L_1 and L_2 and preferences among H_1, H_2, and H_3 scenarios. Participants' performance was assessed not only on Q1 and Q2 but also on their preferences for lighting height and comfortability. This provided an approximate recommendation for the OLH and spectrum quality for non-visual analysis. Statistical methods were applied to obtain significant outcomes from the data and statistically significant data are listed in tables as bold text to clarify that their *p*-values were lower than 0.05.

3.1. Statistical Results of KSS

A *p*-value of 0.05 indicates that there is only a 5% chance that the results observed in the sample occurred by chance [36]. The hypothesis that light affects the rate of sleepiness in occupants, which was tested using the KSS tests, resulted in a Pearson correlation *p*-value of 0.001 for KSS test 1 and KSS test 2. The dataset includes responses from 60 occupants, with KSS survey data collected at both the beginning and end of the survey period.

3.2. Statistical Results of Participants' Performance at H_1, H_2, and H_3 Regarding Age, Gender, and Eye Disorder Factors

The statistical significance of the observed effects on lighting satisfaction, environmental satisfaction, gender, and eye disorders was analyzed using multivariate analysis of variance (MANOVA) tests through Minitab 16 software. The results regarding Q1 and Q2, which include illuminance levels on the desk correlating with performance, are presented in terms of error quantities and the time participants spent during the scenarios. The results listed in Table 5 indicate that environmental lighting satisfaction has a significant effect on the age factor of the participants. Within each of the H_1, H_2, and H_3 conditions, the performance of occupants at each illumination level demonstrates a partial dependence on the age group. Statistically significant data are listed in bold text to emphasize the effective factors, such as gender, eye disorder, and age, on Q1 and Q2 test results and relative heights.

Table 5. Results of MANOVA on illuminance level on the desk with matching performance and proofing test.

MANOVA					p-Value	
Height of Luminaire	**Description**	**Tests**	**Preference**	**Factors**	**L_1**	**L_2**
H_1	illuminance level on the desk/matching performance	Q1	errors	gender	0.36	0.22
				eye disorder	0.76	0.56
				age	0.95	0.54
H_1	illuminance level on the desk/matching performance	Q1	time	gender	0.95	0.32
				eye disorder	0.69	0.28
				age	0.04	0.17
H_1	illuminance level on the desk/proofing test	Q2	errors	gender	0.50	0.58
				eye disorder	0.58	0.19
				age	0.03	0.27
H_1	illuminance level on the desk/proofing test	Q2	time	gender	0.98	0.45
				eye disorder	0.25	0.45
				age	0.10	0.10
H_2	illuminance level on the desk/matching performance	Q1	errors	gender	0.78	0.90
				eye disorder	0.01	0.80
				age	0.19	0.44
H_2	illuminance level on the desk/matching performance	Q1	time	gender	0.10	0.06
				eye disorder	0.20	0.94
				age	0.08	0.02
H_2	illuminance level on the desk/proofing test	Q2	errors	gender	0.69	0.08
				eye disorder	0.77	0.72
				age	0.10	0.04
H_2	illuminance level on the desk/proofing test	Q2	time	gender	0.41	0.45
				eye disorder	0.25	0.44
				age	0.01	0.16
H_3	illuminance level on the desk/matching performance	Q1	errors	gender	0.74	0.34
				eye disorder	0.10	0.43
				age	0.31	0.26
H_3	illuminance level on the desk/matching performance	Q1	time	gender	0.44	0.49
				eye disorder	0.11	0.27
				age	0.16	0.14
H_3	illuminance level on the desk/proofing test	Q2	errors	gender	0.81	0.34
				eye disorder	0.42	0.43
				age	0.94	0.26
H_3	illuminance level on the desk/proofing test	Q2	time	gender	0.63	0.38
				eye disorder	0.08	0.54
				age	0.02	0.10

3.3. Statistical Results of Participants' Performance Levels between H_1, H_2 and H_3

An analysis was conducted on Q1 and Q2 to examine the number of errors and the time taken to complete the tasks (which are defined as Q E LH, and Q t LH). This analysis utilized a *t*-test to provide meaningful insights into the performance levels of occupants at different luminaire heights, H_1, H_2, and H_3. The differences in light beam distributions also became evident, with *p*-values below 0.05 indicating statistical significance. The correlations between the three heights were investigated using the *t*-test, as illustrated in Table 6. The highest correlations were observed between luminaire height and the time taken to complete the tasks. Statistically significant data are listed in bold text to emphasize the effective performance level of occupants at H_1, H_2, and H_3 relatively.

Table 6. Results of *t*-test on performance level of occupants between H_1, H_2, and H_3.

***t*-Test**	***p*-Value**	
Description	$\mathbf{L_1}$	$\mathbf{L_2}$
Q1 E LH_1, Q1 E LH_2	0.704	0.028
Q1 E LH_1, Q1 E LH_3	0.358	0.35
Q1 E LH_2, Q1 E LH_3	0.497	0.132
Q1 t LH_1, Q1 t LH_2	0.208	0.153
Q1 t LH_1, Q1 t LH_3	0.024	0.038
Q1 t LH_2, Q1 t LH_3	0.191	0.5
Q2 E LH_1, Q2 E LH_2	0.305	0.252
Q2 E LH_1, Q2 E LH_3	0.274	0.008
Q2 E LH_2, Q2 E LH_3	0.054	0.036
Q2 t LH_1, Q2 t LH_2	0.346	0.095
Q2 t LH_1, Q2 t LH_3	0.012	0.07
Q2 t LH_2, Q2 t LH_3	0.011	0.511

3.4. Statistical Results of Participants' Performance between L_1 and L_2

In the paired *t*-test, the *p*-values of 0.000 and 0.008 indicate that the data were collected from tests involving the light distribution beam of the luminaires. The *t*-test was applied to assess the difference between L_1 and L_2 lighting conditions. The results supported a distinction in the performance of occupants between L_1H_1 vs. L_2H_1 and L_1H_2 vs. L_2H_2. However, the findings indicated that the lighting conditions of L_1H_3 and L_2H_3 were not significantly different. As shown in Table 7, E refers to the error's quantity and *t* refers the consumed time to answer Q1 and Q2. Statistically significant data are listed in bold text to emphasize the difference between L_1 and L_2 luminaires with relative performance levels.

Table 7. *t*-test applied to test the difference between L_1 and L_2 lighting performances.

Method	**Description**	***p*-Value**
t-test	Paired *t*-test and CI: Q1 E L_1H_1, Q1 E L_2H_1	0.546
	Paired *t*-test and CI: Q1 t L_1H_1 (s), Q1 t L_2H_1 (s)	0
	Paired *t*-test and CI: Q2 E L_1H_1, Q2 E L_2H_1	0.063
	Paired *t*-test and CI: Q2 t L_1H_1 (s), Q2 t L_2H_1 (s)	0.288
	Paired *t*-test and CI: Q1 E L_1H_2, Q1 E L_2H_2	0.117
	Paired *t*-test and CI: Q1 t L_1H_2 (s), Q1 t L_2H_2 (s)	0.095
	Paired *t*-test and CI: Q2 E L_1H_2, Q2 E L_2H_2	0.143
	Paired *t*-test and CI: Q2 t L_1H_2 (s), Q2 t L_2H_2 (s)	0.008
	Paired *t*-test and CI: Q1 E L_1H_3, Q1 E L_2H_3	0.568
	Paired *t*-test and CI: Q1 t L_1H_3 (s), Q1 t L_2H_3 (s)	0.95
	Paired *t*-test and CI: Q2 E L_1H_3, Q2 E L_2H_3	0.052
	Paired *t*-test and CI: Q2 t L_1H_3 (s), Q2 t L_2H_3 (s)	0.35

3.5. Statistical Results of Participants' Performance Dependent on Gender

As the data on participants' gender were not normally distributed, the Mann–Whitney Test was employed to evaluate the difference in performance among occupants under different lighting scenarios [37]. The analysis results are presented in Table 8. Females demonstrated shorter performance times on Q1 L_1H_1 compared to Males, with a sample size of 29 for Females and 31 for Males. Statistically significant data are listed in bold text to emphasize performance levels with the L_1 and L_2 luminaires among both genders.

Table 8. Mann–Whitney Test for applied lighting performance of participants depending on their gender.

Method	Description	*p*-Value
Mann–Whitney Test	Mann–Whitney Test and CI: Q1 E L_1H_1 Female, Q1 E L_1H_1 Male	0.5675
	Mann–Whitney Test and CI: Q1 t L_1H_1 (s) Female, Q1 t L_1H_1 (s) Male	0.8302
	Mann–Whitney Test and CI: Q2 E L_1H_1 Female, Q2 E L_1H_1 Male	0.7106
	Mann–Whitney Test and CI: Q2 t L_1H_1 (s) Female, Q2 t L_1H_1 (s) Male	0.7448
	Mann–Whitney Test and CI: Q1 E L_1H_2 Female, Q1 E L_1H_2 Male	0.8116
	Mann–Whitney Test and CI: Q1 t L_1H_2 (s) Female, Q1 t L_1H_2 (s) Male	**0.0357**
	Mann–Whitney Test and CI: Q2 E L_1H_2 Female, Q2 E L_1H_2 Male	0.6736
	Mann–Whitney Test and CI: Q2 t L_1H_2 (s) Female, Q2 t L_1H_2 (s) Male	0.5944
	Mann–Whitney Test and CI: Q1 E L_1H_3 Female, Q1 E L_1H_3 Male	0.7108
	Mann–Whitney Test and CI: Q1 t L_1H_3 (s) Female, Q1 t L_1H_3 (s) Male	0.2059
	Mann–Whitney Test and CI: Q2 E L_1H_3 Female, Q2 E L_1H_3 Male	0.8463
	Mann–Whitney Test and CI: Q2 t L_1H_3 (s) Female, Q2 t L_1H_3 (s) Male	0.7005
	Mann–Whitney Test and CI: Q1 E L_2H_1 Female, Q1 E L_2H_1 Male	0.2978
	Mann–Whitney Test and CI: Q1 t L_2H_1 (s) Female, Q1 t L_2H_1 (s) Male	0.3004
	Mann–Whitney Test and CI: Q2 E L_2H_1 Female, Q2 E L_2H_1 Male	0.9109
	Mann–Whitney Test and CI: Q2 t L_2H_1 (s) Female, Q2 t L_2H_1 (s) Male	0.7005
	Mann–Whitney Test and CI: Q1 E L_2H_2 Female, Q1 E L_2H_2 Male	0.6322
	Mann–Whitney Test and CI: Q1 t L_2H_2 (s) Female, Q1 t L_2H_2 (s) Male	0.1169
	Mann–Whitney Test and CI: Q2 E L_2H_2 Female, Q2 E L_2H_2 Male	0.2710
	Mann–Whitney Test and CI: Q2 t L_2H_2 (s) Female, Q2 t L_2H_2 (s) Male	0.9646
	Mann–Whitney Test and CI: Q1 E L_2H_3 Female, Q1 E L_2H_3 Male	0.1035
	Mann–Whitney Test and CI: Q1 t L_2H_3 (s) Female, Q1 t L_2H_3 (s) Male	0.2936
	Mann–Whitney Test and CI: Q2 E L_2H_3 Female, Q2 E L_2H_3 Male	0.2370
	Mann–Whitney Test and CI: Q2 t L_2H_3 (s) Female, Q2 t L_2H_3 (s) Male	0.7337

3.6. Statistical Results of Participants' Performance Regarding Age Groups

As the data on participants' age groups were not normally distributed, as in Section 3.5, the Mann–Whitney Test was utilized to evaluate the difference in performance among occupants under the lighting scenarios. The results of the analysis are presented in Table 9. Performance is categorized based on the age groups of the participants, with a sample size of 22 for those aged 20–30 years, 20 for those aged 30–40 years, and 18 for those aged 40 years and older. Statistically significant data are listed in bold text to emphasize performance levels with the L_1 and L_2 luminaires at H_1, H_2, H_3 among the age groups.

Table 9. Mann–Whitney Test for applied lighting performances of participants depending on the age groups.

Method	Description	*p*-Value
Mann–Whitney Test	Q1 E L_1H_1 20–30, Q1 E L_1H_1 30–40	0.8848
	Q1 t L_1H_1 (s) 20–30, Q1 t L_1H_1 (s) 30–40	0.0098
	Q2 E L_1H_1 20–30, Q2 E L_1H_1 30–40	0.0117
	Q2 t L_1H_1 (s) 20–30, Q2 t L_1H_1 (s) 30–40	0.1548
	Q1 E L_1H_2 20–30, Q1 E L_1H_2 30–40	0.3872
	Q1 t L_1H_2 (s) 20–30, Q1 t L_1H_2 (s) 30–40	0.6963
	Q2 E L_1H_2 20–30, Q2 E L_1H_2 30–40	0.3993
	Q2 t L_1H_2 (s) 20–30, Q2 t L_1H_2 (s) 30–40	0.0453
	Q1 E L_1H_3 20–30, Q1 E L_1H_3 30–40	0.2652
	Q1 t L_1H_3 (s) 20–30, Q1 t L_1H_3 (s) 30–40	0.0990
	Q2 E L_1H_3 20–30, Q2 E L_1H_3 30–40	0.7748
	Q2 t L_1H_3 (s) 20–30, Q2 t L_1H_3 (s) 30–40	0.0333
	Q1 E L_2H_1 20–30, Q1 E L_2H_1 30–40	0.2235
	Q1 t L_2H_1 (s) 20–30, Q1 t L_2H_1 (s) 30–40	0.0068
	Q2 E L_2H_1 20–30, Q2 E L_2H_1 30–40	0.3530
	Q2 t L_2H_1 (s) 20–30, Q2 t L_2H_1 (s) 30–40	0.0642

Table 9. *Cont.*

Method	Description	*p*-Value
	Q1 E L_2H_2 20–30, Q1 E L_2H_2 30–40	0.6219
	Q1 t L_2H_2 (s) 20–30, Q1 t L_2H_2 (s) 30–40	0.0572
	Q2 E L_2H_2 20–30, Q2 E L_2H_2 30–40	0.9884
	Q2 t L_2H_2 (s) 20–30, Q2 t L_2H_2 (s) 30–40	0.3198
	Q1 t L_2H_3 (s) 20–30, Q1 t L_2H_3 (s) 30–40	0.0333
	Q2 E L_2H_3 20–30, Q2 E L_2H_3 30–40	0.4599
	Q2 t L_2H_3 (s) 20–30, Q2 t L_2H_3 (s) 30–40	0.1946
	Q1 E L_1H_1 20–30, Q1 E L_1H_1 40+	0.7760
	Q1 t L_1H_1 (s) 20–30, Q1 t L_1H_1 (s) 40+	0.0685
	Q2 E L_1H_1 20–30, Q2 E L_1H_1 40+	0.0489
	Q2 t L_1H_1 (s) 20–30, Q2 t L_1H_1 (s) 40+	0.0553
	Q1 E L_1H_2 20–30, Q1 E L_1H_2 40+	0.3888
	Q1 t L_1H_2 (s) 20–30, Q1 t L_1H_2 (s) 40+	0.0375
	Q2 E L_1H_2 20–30, Q2 E L_1H_2 40+	0.4040
	Q2 t L_1H_2 (s) 20–30, Q2 t L_1H_2 (s) 40+	0.0119
	Q1 E L_1H_3 20–30, Q1 E L_1H_3 40+	0.9140
	Q1 t L_1H_3 (s) 20–30, Q1 t L_1H_3 (s) 40+	0.0375
	Q2 E L_1H_3 20–30, Q2 E L_1H_3 40+	0.9749
	Q2 t L_1H_3 (s) 20–30, Q2 t L_1H_3 (s) 40+	0.0129
	Q1 E L_2H_1 20–30, Q1 E L_2H_1 40+	0.4659
	Q1 t L_2H_1 (s) 20–30, Q1 t L_2H_1 (s) 40+	0.2264
	Q2 E L_2H_1 20–30, Q2 E L_2H_1 40+	0.1557
	Q2 t L_2H_1 (s) 20–30, Q2 t L_2H_1 (s) 40+	0.0216
	Q1 t L_2H_2 (s) 20–30, Q1 t L_2H_2 (s) 40+	0.0110
	Q2 E L_2H_2 20–30, Q2 E L_2H_2 40+	0.4141
Mann–Whitney Test	Q2 t L_2H_2 (s) 20–30, Q2 t L_2H_2 (s) 40+	0.0945
	Q1 t L_2H_3 (s) 20–30, Q1 t L_2H_3 (s) 40+	0.0328
	Q2 E L_2H_3 20–30, Q2 E L_2H_3 40+	0.1210
	Q2 t L_2H_3 (s) 20–30, Q2 t L_2H_3 (s) 40+	0.0286
	Q1 E L_1H_1 30–40, Q1 E L_1H_1 40+	0.9083
	Q1 t L_1H_1 (s) 30–40, Q1 t L_1H_1 (s) 40+	0.4472
	Q2 E L_1H_1 30–40, Q2 E L_1H_1 40+	0.6114
	Q2 t L_1H_1 (s) 30–40, Q2 t L_1H_1 (s) 40+	0.5786
	Q1 t L_1H_2 (s) 30–40, Q1 t L_1H_2 (s) 40+	0.1438
	Q2 E L_1H_2 30–40, Q2 E L_1H_2 40+	0.9372
	Q2 t L_1H_2 (s) 30–40, Q2 t L_1H_2 (s) 40+	0.4299
	Q1 E L_1H_3 30–40, Q1 E L_1H_3 40+	0.3643
	Q1 t L_1H_3 (s) 30–40, Q1 t L_1H_3 (s) 40+	1
	Q2 E L_1H_3 30–40, Q2 E L_1H_3 40+	0.7666
	Q2 t L_1H_3 (s) 30–40, Q2 t L_1H_3 (s) 40+	0.6610
	Q1 E L_2H_1 30–40, Q1 E L_2H_1 40+	0.6182
	Q1 t L_2H_1 (s) 30–40, Q1 t L_2H_1 (s) 40+	0.2794
	Q2 E L_2H_1 30–40, Q2 E L_2H_1 40+	0.6397
	Q2 t L_2H_1 (s) 30–40, Q2 t L_2H_1 (s) 40+	0.9534
	Q1 t L_2H_2 (s) 30–40, Q1 t L_2H_2 (s) 40+	0.4648
	Q2 E L_2H_2 30–40, Q2 E L_2H_2 40+	0.4608
	Q2 t L_2H_2 (s) 30–40, Q2 t L_2H_2 (s) 40+	0.5392
	Q1 E L_2H_3 30–40, Q1 E L_2H_3 40+	0.3448
	Q1 t L_2H_3 (s) 30–40, Q1 t L_2H_3 (s) 40+	0.9767
	Q2 E L_2H_3 30–40, Q2 E L_2H_3 40+	0.4429
	Q2 t L_2H_3 (s) 30–40, Q2 t L_2H_3 (s) 40+	0.5587

3.7. *Results of the Observed Prevalence of H_1, H_2, and H_3 and L_1 and L_2*

In terms of the performance level of the 60 participants, the best performance was observed at L_1H_3 and L_2H_2, as shown in Table 10. Participants achieved their highest performance at H_3 for L_1 and H_2 for L_2 among H_1, H_2, and H_3. Hence, the best case is L_1H_3 due to the test results and participants' preferences for scenarios.

Table 10. Comparison of participants' performance levels for L_1 and L_2 under each condition, H_1, H_2, and H_3.

Luminaire/Height	ERROR		TIME	
	Matching Performance	Visual Proof	Matching Performance	Visual Proof
L_1H_1	✓	✓✓	✓	✓✓
L_1H_2	✓✓	✓	✓✓	✓
L_1H_3	✓✓✓	✓✓✓	✓✓✓	✓✓✓
L_2H_1	✓	✓✓✓	✓✓✓	✓
L_2H_2	✓✓	✓✓	✓✓✓	✓✓
L_2H_3	✓✓	✓	✓	✓✓✓

✓: The worse performance results; ✓✓: moderate performance results; ✓✓✓: the best performance results.

The comfort criteria of the participants were also important in this study. Although H_3 is the most preferred luminaire height among H_1, H_2, and H_3 for L_1 and L_2 in Table 11, the performance of the participants is more successful at H_2 of L_2 in comparison with H_1 and H_3, as shown in Table 10.

Table 11. Comparison of the preference level of participants between L_1 and L_2 under each condition, H_1, H_2, H_3.

Luminaire /Height	Satisfaction with Lighting	There Is Appropriate Lighting to Perform the Task	Color of Light Is Appealing	Lighting Bothered You during Task	Lighting Is Unified on the Desk	Mounting Height of Lighting Is Appropriate
L_1H_1	✓	✓✓✓	✓✓✓	✓	✓✓✓	✓
L_1H_2	✓✓	✓	✓✓	✓✓✓	✓	✓✓
L_1H_3	✓✓✓	✓✓	✓	✓✓	✓✓	✓✓✓
L_2H_1	✓✓	✓✓	✓✓✓	✓	✓✓✓	✓
L_2H_2	✓	✓	✓	✓✓	✓	✓✓
L_2H_3	✓✓✓	✓✓✓	✓✓	✓✓✓	✓✓	✓✓✓

✓ : the worse performance results; ✓✓ : moderate performance results; ✓✓✓ : the best performance results.

3.8. Statistical Results of Participants' Preference between L_2H_2 and L_1H_3

Regarding this Section, the evaluation of the most successful scenarios, L_1H_3 and L_2H_2, aimed to observe the differences in lighting scenarios between the two. The most favorable scenario is observed in L_1H_3 not only in performance but also in the preferences expressed by the participants. Conversely, the results of L_2H_2 indicate that while participants' performance was successful, their preference was lower compared to L_2H_3. An analysis of variance (ANOVA) was applied to the data, and the results are presented in Table 12. The analysis indicates a statistically significant difference in the satisfaction level of lighting, a suitable illuminance level on the desk, uniformity of lighting, pleasantness of the light color, unpleasantness of lighting during tests, and the height of the lighting between L_1 and L_2. Statistically significant data are listed in bold text to evaluate the preference level between L_1H_3 and L_2H_2.

Table 12. Prevalence rate of participants' preference between L_1H_3 and L_2H_2.

Method	Description	*p*-Value
ANOVA	Satisfaction with lighting at scenarios L_1H_3 versus L_2H_2	0.014
	There is appropriate lighting to perform the task versus at scenarios L_1H_3 versus L_2H_2	0.016
	Color of light is appealing versus at scenarios L_1H_3 versus L_2H_2	0.085
	Lighting bothered you during performing the tasks at scenarios L_1H_3 versus L_2H_2	0.425
	Lighting is unified on desk at scenarios L_1H_3 versus L_2H_2	0.011
	Mounting height of lighting is suitable at scenarios L_1H_3 versus L_2H_2	0.79

4. Discussion

Changes in lighting levels, psychological comfort, and performance were examined by using H_1–H_2–H_3 values on L_1 and L_2. To assess the impact of lighting level changes on psychological comfort, participants were asked a series of questions in six different lighting scenarios for office environments. The responses due to the tests indicated that L_1H_3 and L_2H_2 were considered the most suitable cases.

This study conducted an experiment in a setup considered "appropriate" for exploring human-centered lighting conditions in addition to physiological comfort conditions. Q1 and Q2 were queried for each participant during the survey, while error quantities and consumed time periods served as measurement scales, alongside the occupants' preferences based on their comfort criteria. The results, focusing on light levels, luminaire positions, and light distribution beams, are summarized as follows:

Matching the performance and visual perception of participants not only in L_1H_1 Q1 E with a *p*-value of 0.04, L_1H_1 Q2 E with a *p*-value of 0.03, L_2H_2 Q1 t with a *p*-value of 0.02, L_2H_2 Q2 E with a *p*-value of 0.04, L_2H_2 Q2 t with a *p*-value of 0.01, and L_1H_3 Q2 t with a *p*-value of 0.02, among gender, eye disorder, and age factors, but also in L_1H_2 Q1 E eye disorder with a *p*-value of 0.01 rejects the null hypothesis that age and eye disorder are not effective for the performance of participants.

The performance evaluation results of participants were compared between H_1, H_2, and H_3. For L_1, the *p*-values for H_1 and H_3 Q1 t were 0.024, those for H_1 and H_3 Q2 t were 0.012, and those for H_2 and H_3 Q2 t were 0.011. For L_2, the *p*-values for H_1 and H_2 Q1 E were 0.028, those for H_1 and H_3 Q2 E were 0.008, and those for H_2 and H_3 Q2 E were 0.036. These *p*-values reject the null hypotheses that there is no difference in performance regarding the variation in heights.

The impact of difference on L_1 and L_2 with the point of view of performance in H_1, H_2, and H_3 was measured. According to the test results at a significance level of *p*-value lower than 0.05, significant differences were found in the response times for Q1 in L_1H_1 and L_2H_1 and for Q2 in L_1H_2 and L_2H_2.

The comparison of participants' performance results between L_1 and L_2, performed on Q1 and Q2 t, shows that the null hypotheses are rejected for H_1 and H_2, but approved for H_3, which shows that L_1 and L_2 at H_3 present similar data.

The relationship between gender and visual impairment with performance based on changes in light levels was not significant at a significance level of *p*-value 0.05. The age factor showed a significant relationship with performance based on changes in light levels, specifically between the age groups 20–30 and 30–40 and between 20–30 and 40 and above.

When evaluating the adequacy of light levels, participants favored L_1H_1 and L_2H_3. L_1 received higher preferences at all three heights due to differences in the distribution of lighting beams. The test results showed that perceived differences in lighting levels influenced personal impressions of psychological comfort. Improvements in physical comfort conditions, such as the higher height of lighting, were viewed as positive. Uniformity was achieved in both L_1 and L_2, but in L_2H_2, a lower level compared to other scenarios was noted.

According to the study results, a generalization such as "increasing light levels improves performance" cannot be made. The test results indicate that L_1H_3 and L_2H_2 are the most successful scenarios. L_1H_3 has the values as E_H: 752.5 lux; E_v: 550 lux and L_2H_2 has the values as E_h: 520 lux; E_V: 393 lux which meets the minimum requirements of CS and EML values.

In terms of satisfaction, participants expressed the highest satisfaction in scenarios L_1H_3 and L_2H_3. An interesting finding of this study was the achieved high performance in L_1H_3 and L_2H_2. At H_2, a 40% power saving was proposed for both L_1 and L_2, but our proposal for an energy-efficient lighting scenario based on the light beam distribution and SPD of the luminaires was ignored in L_1H_3 due to the participants' performance and feedback. On the other hand, successful performances were recorded in L_2H_2, while participants' satisfaction comments were low. The performance of office workers is highly dependent on age groups, as recorded in the test results. These comments align with the performance situation in L_1H_3, but energy efficiency was not achieved. While the satisfaction rate was highest in L_1H_3, participants performed better in L_2H_2, and energy efficiency gained significance. Therefore, between L_1H_3 and L_2H_2, participant satisfaction with light levels, given adequate light levels and uniformity on the working desk, was found to be significant.

Mounting height emerged as a crucial variable, so research could aim to mitigate the influence of height selections on subjective assessments. Part 2 of our study concentrates on investigating effective scenarios with varying CCT selections, considering the adaptable nature of CCT in human-centered lighting.

5. Conclusions

This study detailed the lighting design process in the design development phase and provided summaries of relevant circadian lighting metrics, simulation tools, energy considerations, and the research plan for the circadian lighting open-plan office. Providing the necessary E_V levels at eye level for occupants can be challenging to achieve with traditional ceiling-recessed luminaire technology. In this study, the trade-offs between optical distributions and color tuning options limited the selection of luminaires that could meet the desired experimental lighting conditions. Designing to meet the recommended thresholds of EML and CS throughout the open-plan office resulted in horizontal and vertical illuminance levels in line with the recommendations from the IES for visual tasks. This paper discussed the experimental aspect of open-plan office lighting for circadian impact and investigated occupant responses to office lighting through a field study. In this field study, 60 participants with office worker characteristics completed visual performance tests and provided judgments regarding their alertness, mood, lighting and environmental satisfaction, and feelings of sleepiness. The results suggest that occupants performed better with the Direct Linear Suspended Lighting luminaire (L_1) at a height of 2.3 m (H_3) above the finished floor and Direct and Indirect Linear Suspended Lighting luminaire (L_2) at a height of 1.8 m (H_2) above the finished floor in the open-plan office environmental conditions. According to these results, it is understood that lighting installations that meet the necessary conditions for HCL can be created with appropriate photometric luminaires and appropriate mounting mechanisms.

This study presents a comprehensive evaluation of the non-visual aspects of open-plan office lighting environments, offers suggestions for non-visual indoor lighting design, and establishes acceptable approximation laws for eye-level SPDs and mounting heights. However, it is premature to recommend a widely accepted method for evaluating non-visual effects. There are still many unresolved issues in this research field, particularly regarding the applicability of non-visual calculation models, which form the basis of CCT variation. Therefore, further research in Part 2 is necessary to gain a full understanding of the non-visual effects of indoor light environments with different CCT options.

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Appendix A. First Step of Survey

	How do you currently feel? Please mark the most suitable option	
1	Extremely alert	
	Very alert	
	Alert	
	Quite alert	
	Neither alert nor sleepy	
	Some signs of sleepiness	
	Sleepy but not making an effort to stay awake	
	Sleepy but making some effort to stay awake	
	Very sleepy, making a considerable effort to stay awake, fighting sleep	
	Extremely sleepy, unable to stay awake	

		Very poor	Poor	Moderate	Good	Very good
2	How satisfied are you with the overall comfort of your office furniture (chair, desk, equipment arrangement, etc.)?					
	How satisfied are you with the available space for desk/individual work arrangement?					

3	What is your age group?	20-30	30-40	40+

4	What is your gender?	Female	Male

5	Do you wear contact lenses or glasses or if you have any eye disorder, please specify.	Yes	No

		Very poor	Poor	Moderate	Good	Very good
6	Do you feel concentrated?					
	Do you feel nervous?					
	Do you feel inspired?					
	Do you feel determined?					
	Do you feel afraid?					
	Do you feel upset?					
	Do you feel ashamed?					
	Do you feel physically well right now?					
	Do you feel mentally well right now?					
	Do you feel motivated to complete the task that you are currently working on?					

Figure A1. KSS1 test and general information with PANAS Questionnaires.

Appendix B. Second Step of Survey: Visual Tests Q1 and Q2

Please answer the tests as quickly as possible. Match the letters in the left column with those in the right column.

L1

	H1				H2				H3		
1	SCBP	PBBP	......	**1**	BP659	SCBP	......	**1**	BP659	BSOP	......
2	PCSS	BB999	......	**2**	PP999	PCSS	......	**2**	PP999	SCBP	......
3	BSOP	PB555	......	**3**	SCBP	BSOP	......	**3**	SCBP	BCSS	......
4	BP659	BB969	......	**4**	BB999	BP659	......	**4**	BB999	PP999	......
5	BCSS	SSPB	......	**5**	PBBP	BCSS	......	**5**	PBBP	PCSS	......
6	GCOD	PB595	......	**6**	BB969	GCOD	......	**6**	BB969	BB969	......
7	PP999	SSCC	......	**7**	SSCC	PP999	......	**7**	SSCC	PBBP	......
8	BB999	BP595	......	**8**	BP595	BB969	......	**8**	BP595	BP659	......
9	BP999	BP999	......	**9**	PCSS	BP999	......	**9**	PCSS	BP999	......
10	BB969	PB559	......	**10**	BP999	BB999	......	**10**	BP999	SSPB	......
11	PBBP	PB556	......	**11**	SSPB	PBBP	......	**11**	SSPB	BP595	......
12	SSCC	00CC	......	**12**	BCSS	SSCC	......	**12**	BCSS	GCOD	......
13	BP595	SCBO	......	**13**	PB555	BP595	......	**13**	PB555	BB999	......
14	PB555	PP999	......	**14**	PB595	PB555	......	**14**	PB595	SSCC	......
15	PB556	SCBP	......	**15**	BSOP	PB556	......	**15**	BSOP	PB559	......
16	PB595	GCOD	......	**16**	PB556	PB595	......	**16**	PB556	SCBO	......
17	SSPB	BSOP	......	**17**	SCBO	SSPB	......	**17**	SCBO	PB555	......
18	PB559	BP659	......	**18**	GCOD	PB559	......	**18**	GCOD	00CC	......
19	SCBO	PCSS	......	**19**	PB559	SCBO	......	**19**	PB559	PB556	......
20	00CC	BCSS	......	**20**	00CC	00CC	......	**20**	00CC	PB595	......

Completion time: ...... **Completion time: ......** **Completion time: ......**

Please answer the tests as quickly as possible. Match the letters in the left column with those in the right column.

L2

	H1				H2				H3		
1	SCBP	BSOP	......	**1**	PBBP	BSOP	......	**1**	GCOD	PBBP	......
2	PCSS	SCBP	......	**2**	BB999	SCBP	......	**2**	PP999	BB999	......
3	BSOP	BCSS	......	**3**	PB555	BCSS	......	**3**	BB999	PB555	......
4	BP659	PP999	......	**4**	BB969	PP999	......	**4**	BSOP	BB969	......
5	BCSS	PCSS	......	**5**	SSPB	PCSS	......	**5**	PBBP	SSPB	......
6	GCOD	BB969	......	**6**	PB595	BB969	......	**6**	SCBP	PB595	......
7	PP999	PBBP	......	**7**	SSCC	PBBP	......	**7**	BP595	SSCC	......
8	BB999	BP659	......	**8**	BP595	BP659	......	**8**	SSCC	BP595	......
9	BP999	BP999	......	**9**	BP999	BP999	......	**9**	PCSS	BP999	......
10	BB969	SSPB	......	**10**	PB559	SSPB	......	**10**	PB555	PB559	......
11	PBBP	BP595	......	**11**	PB556	BP595	......	**11**	SSPB	PB556	......
12	SSCC	GCOD	......	**12**	00CC	GCOD	......	**12**	BP659	00CC	......
13	BP595	BB999	......	**13**	SCBO	BB999	......	**13**	BCSS	SCBO	......
14	PB555	SSCC	......	**14**	PP999	SSCC	......	**14**	PB556	PP999	......
15	PB556	PB559	......	**15**	SCBP	PB559	......	**15**	PB559	SCBP	......
16	PB595	SCBO	......	**16**	GCOD	SCBO	......	**16**	SCBO	GCOD	......
17	SSPB	PB555	......	**17**	BSOP	PB555	......	**17**	PB595	BSOP	......
18	PB559	00CC	......	**18**	BP659	00CC	......	**18**	BP999	BP659	......
19	SCBO	PB556	......	**19**	PCSS	PB556	......	**19**	00CC	PCSS	......
20	00CC	PB595	......	**20**	BCSS	PB595	......	**20**	BB969	BCSS	......

Completion time: ...... **Completion time: ......** **Completion time: ......**

Figure A2. Q1 Visual Cognitive Matching Performance Test.

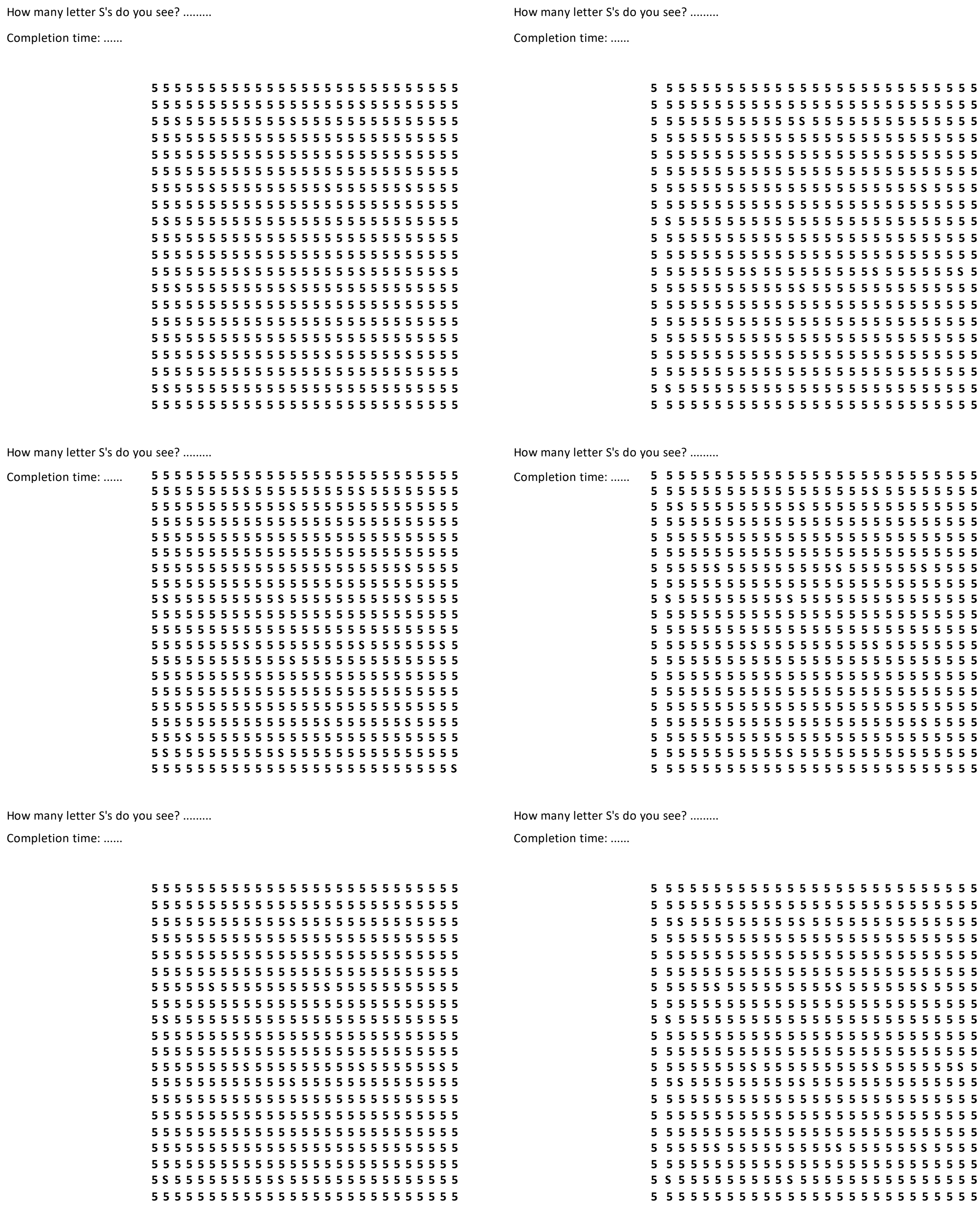

Figure A3. Q2 Visual Proofreading Task Test.

Appendix C. Third Step of Survey

Please respond to your preferences from the options below.

L1

	Very Poor	Poor	Moderate	Good	Very Good
I am satisfied with the current lighting.					
There is an appropriate level of lighting for the task I am currently doing.					
I am satisfied with the color of the light.					
The lighting has bothered during the task.					
The lighting is adequate on my work desk.					

Is the lighting height suitable for you (H1)?	Yes	No
Note: (Do you have any additional suggestions to add)?		

	Very Poor	Poor	Moderate	Good	Very Good
I am satisfied with the current lighting.					
There is an appropriate level of lighting for the task I am currently doing.					
I am satisfied with the color of the light.					
The lighting has bothered during the task.					
The lighting is adequate on my work desk.					

Is the lighting height suitable for you (H2)?	Yes	No
Note: (Do you have any additional suggestions to add)?		

	Very Poor	Poor	Moderate	Good	Very Good
I am satisfied with the current lighting.					
There is an appropriate level of lighting for the task I am currently doing.					
I am satisfied with the color of the light.					
The lighting has bothered during the task.					
The lighting is adequate on my work desk.					

Is the lighting height suitable for you (H3)?	Yes	No
Note: (Do you have any additional suggestions to add)?		

Please respond to your preferences from the options below.

L2

	Very Poor	Poor	Moderate	Good	Very Good
I am satisfied with the current lighting.					
There is an appropriate level of lighting for the task I am currently doing.					
I am satisfied with the color of the light.					
The lighting has bothered during the task.					
The lighting is adequate on my work desk.					

Is the lighting height suitable for you (H1)?	Yes	No
Note: (Do you have any additional suggestions to add)?		

	Very Poor	Poor	Moderate	Good	Very Good
I am satisfied with the current lighting.					
There is an appropriate level of lighting for the task I am currently doing.					
I am satisfied with the color of the light.					
The lighting has bothered during the task.					
The lighting is adequate on my work desk.					

Is the lighting height suitable for you (H2)?	Yes	No
Note: (Do you have any additional suggestions to add)?		

	Very Poor	Poor	Moderate	Good	Very Good
I am satisfied with the current lighting.					
There is an appropriate level of lighting for the task I am currently doing.					
I am satisfied with the color of the light.					
The lighting has bothered during the task.					
The lighting is adequate on my work desk.					

Is the lighting height suitable for you (H3)?	Yes	No
Note: (Do you have any additional suggestions to add)?		

Figure A4. Feedbacks of participants at each lighting scenarios.

Appendix D. Forth Step of Survey

How do you currently feel? Please mark the most suitable option from the follow-ing list:	
Extremely alert	
Very alert	
Alert	
Quite alert	
Neither alert nor sleepy	
Some signs of sleepiness	
Sleepy but not making an effort to stay awake	
Sleepy but making some effort to stay awake	
Very sleepy, making a considerable effort to stay awake, fighting sleep	
Extremely sleepy, unable to stay awake	

Figure A5. KSS2 Questionnaire. Reprinted/adapted with permission from Ref. [18].

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