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Exploring the relationship between office lighting, cognitive performance, and psychophysiological responses: A multidimensional approach

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ABSTRACT

Recognizing the growing importance of optimizing work environments for better cognitive performance, this study examined the relationships between general office lighting, psychophysiological responses and cognitive performance. Sixteen healthy adults in their 20s participated in experiments under nine different lighting conditions combining three levels of correlated color temperature (i.e., 4,000K, 5,000K, and 6,500K) and three levels of illuminance (i.e., 200 lx, 500 lx, and 800 lx). In the experiments, subjects' primary and complex cognitive performances were measured and their psychophysiological responses such as mental workload, drowsiness, mental fatigue and stress, and visual fatigue were evaluated. Statistical analyses revealed that higher correlated color temperature and illuminance significantly enhanced primary cognitive performance but did not significantly impact complex cognitive performance or most psychophysiological responses. Notably, psychophysiological responses and cognitive performances were found to have mutual relationships rather than one being an absolute independent variable for another. The study suggests that tailored smart lighting systems could enhance cognitive performance in office environments by dynamically adjusting lighting conditions based on real-time psychophysiological feedback.

1. Introduction

Unlike the past, in most modern offices, working without light is not impossible though a bit difficult. This change has been facilitated by the use of computers, smart tablets, and phones for work. The Federal Reserve Bank of Atlanta reported that 92 % of jobs require digital skills, and currently most of the population that works in an office seems to use digital devices such as computers or smart tablets [1,2]. Because these digital devices' self-emitting displays can act as a light source, modern offices are less dependent on artificial lighting to ensure visibility than in the past, when office work was mainly carried out on paper [3,4]. Moreover, as research is actively conducted regarding the effects of lighting on occupants' general health, including their mood, the role and scope of lighting has gradually extended from its original function of merely providing illumination [5,6]. Based on research results, the demand for lighting to implement personalized lighting control and occupants' well-being has increased. Consequently, the smart lighting market recorded USD 15.05 billion as of 2022 and is expected to achieve a compound annual growth rate of 22.1 % by 2030 [7]. Among the many roles lighting plays, lighting design for an office should consider productivity a priority. The traditional office lighting design mainly considered ensuring sufficient visibility for work performance and energy efficiency. However, as the impact of lighting is further investigated, research has been conducted on a lighting environment that can maximize cognitive performance.

The impact of lighting on cognitive performance was investigated using a method to measure productivity in an office or learning efficiency in an educational facility. Sun et al. (2019) performed various cognitive tests on perception, memory, thinking and executive functions in a lit environment with illuminance levels of 100–2500 lx and correlated color temperature values of 2700–6500 K [8]. Zeng et al. (2022) measured three types of productivity (i.e., arithmetical ability, memory and perception) according to a CCT in a lit environment at 4000–10, 000K [5]. Liu et al. (2010) discovered that when work was done using a digital display at 200lx and 500lx, productivity was higher at 200lx [9]. In these studies, it was observed that productivity improves with increased illuminance and CCT. On the other hand, Yang and Jeon (2020) reported that when a subject's memory was measured at illuminance levels of 650lx and 1,050lx and CCT values of 3,000K, 4,000K and 5,700K, there was no difference in memory according to CCT and illuminance [10]. In addition, Wang et al. (2014) evaluated reading

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Abbreviations

AUT	Alternative uses task
BA	Blink amplitude
CCA	Canonical correlation analysis
CCT	Correlated color temperature
DR	Drowsiness
ECG	Electrocardiography
EEG	Electroencephalography
EOG	Electrooculography
KSS	Karolinska sleepiness scale
LED	Lighting emitting diode
MFS	Mental fatigue and stress
MHR	Mean heart rate
MLM	Mixed linear model
MRA	Multiple regressions analysis
MWL	Mental workload
NASA-TLX	National Aeronautics and Space Administration task load index
PCA	Principal correlation analysis
PUI	Pupillary unrest index
RMSSD	Root mean square of successive differences
SDNN	Standard deviation of NN intervals
VF	Visual fatigue

performance under various light emitting diode (LED) lights and found that there was no effect from illuminance or CCT [11]. Likewise, studies have been carried out to measure cognitive performance on subjects' productivity or learning efficiency in a wide range of illuminance and CCT. However, it was confirmed that in most of the previous research, extreme lighting conditions were used. According to the standard EN 12464-1 or the US Occupational Health and Safety Administration, the recommended illuminance for an office is around 500lx [12]. However, in most of the previous studies, an experimental environment was established with a very large variance, given the recommended illuminance, and there was diversity so that subjects could clearly distinguish even in the case of CCT with no clear recommended range or standards. This diversity has the advantage of being able to identify differences in cognitive performance under various lighting conditions. However, since most office lighting does not vary that much, it is difficult to determine whether general office lighting has a significant impact on cognitive performance in reality. Moreover, most of the previous studies posed limitations that measure cognitive performance, targeting only a few types of abilities. As a result, there was a lack of research to consider both primary cognitive performance and tasks that mimic those performed in an actual office in tests and analyze the test results.

Cognitive performance is a high-level concept not directly and solely influenced by the indoor environment. According to Choi et al. (2023), cognitive performance is not directly affected by indoor environmental quality but indirectly affected by physiological and psychological responses [13]. In this manner, one of the reasons why lighting has been more actively examined in research on cognitive performance compared to other indoor environment factors is because lighting is highly related to various factors affecting cognitive performance, such as occupants' mood, eye fatigue or alertness [14–16]. Several studies have therefore been undertaken to measure occupants' physiological or psychological responses according to lighting and to determine the relationship between them [17]. However, only a few studies addressed the complex relationship with cognitive performance. Consequently, in order to lay a foundation for developing smart lighting technology available to actual office environments, more comprehensive research is required. Therefore, this study investigates relationships between general office lighting, psychophysiological responses, and various types of cognitive performances. To achieve the aim of the research, two research questions have been established:

(1) *Research question 1: How does general office lighting impact psychophysiological responses and cognitive performance?*
(2) *Research question 2: How do psychophysiological responses and cognitive performance affect each other?*

To explore the research questions, experiments were conducted on human subjects under nine general office lighting settings. Data collected in the experiments were preprocessed and integrated indices were derived from the raw data for efficient data analysis. Statistical approaches were applied to investigate the relationships between general office lighting settings, psychophysiological responses, and cognitive performance.

2. Materials and methods

In this study, subjects' psychophysiological responses and cognitive performance in various office lighting environments were measured and then the relationships between the three elements (i.e., lighting, psychophysiological and cognitive performance) were analyzed through a statistical approach.

2.1. Measurement

To measure the subjects' psychophysiological responses, their physiological responses and psychological responses were measured using both equipment and surveys. Additionally, subjects' cognitive performances were measured using various tests.

2.1.1. Psychophysiological responses

This study defines four possible psychophysiological responses from the occupants of an office: (i) mental workload (MWL), (ii) drowsiness (DR), (iii) mental fatigue and stress (MFS) and (iv) visual fatigue (VF). MWL is the amount of mental effort required to perform a task and represents the degree of cognitive stress or pressure that an individual undergoes while performing a task [18]. Bao et al. (2021) measured MWL under different lighting environments where CCT and illuminance varied, and MWL was evaluated using electroencephalography data and National Aeronautics and Space Administration task load index (NASA-TLX) assessment [19]. In this study, it was found that MWL reaches minimum point under environment of 3,000K and 750lx. DR is a phenomenon caused by fatigue or lack of sleep and results in a reduction in alertness [20]. In the previous study, wall luminance was found to have an impact on subjective DR, and from this result, it can be inferred that higher illuminance can reduce DR [21]. MFS refers to brain fatigue and response to mental demands [22]. Electrocardiography and subjective evaluation were used to evaluate MFS in different lighting environments, and it was found that higher illuminance is more preferred although there was not significant difference in MFS between standard and personalized lighting [23]. Lastly, VF represents phenomena such as eye discomfort and vision problems [24]. It was found that cooler CCT was more effective to reduce VF, and illuminance also significantly affects VF in the previous study [11]. To measure these psychophysiological responses, objective and subjective indices were collected via equipment and surveys, respectively. Objective indices are physiological responses and refer to various bio-signals that arise regardless of the subjects' intention, while subjective indices refer to self-reported survey responses from the subjects who evaluate their own conditions.

2.1.1.1. Physiological responses. To objectively measure psychophysiological responses, data were collected using four types of equipment (refer to Fig. 1).

- ***Electroencephalography (EEG):*** EEG is a non-invasive method for measuring the electrical activities of the brain with active electrodes attached to the scalp, and can also measure brain waves in the cerebral cortex [25]. Brain waves are electrical flows that occur when neurons are active and can be categorized into several types depending on the frequency band [26]. In this study, delta, theta, alpha and beta waves were collected from the frontal, temporal, parietal and occipital lobes. To collect brain waves, an EEG electrode cap, a product from Biopac Systems, was used [27]. Furthermore, electrooculography (EOG) was used to measure the electrical activity of the retina based on the electrical distance between the pupil and the retina. The electrical activity of the eye was used to remove artifacts from data measured by EEG [28].
- ***Electrocardiography (ECG):*** ECG is a non-invasive method designed to measure the electrical activity that occurs with every beat of the heart [29]. To do this, electrodes were attached to the right upper arm, the left upper arm and the lower left side of the abdomen. ECG equipment from Biopac Systems was also used. Indicators such as mean heart rate (MHR), standard deviation of NN intervals (SDNN) and the root mean square of successive differences (RMSSD) can be derived from the ECG data.
- ***Eye tracking glasses:*** The subject's pupil size and eye validity data were collected using Tobii Glasses 3 from Tobii Technology [16]. Pupillary unrest index (PUI) can be extracted via the pupil size [30], and eye validity data can be used to derive blink amplitude (BA) [31]. PUI is an index to measure changes in the pupil diameter and is affected by various factors such as the activity of the autonomic nervous system. BA refers to the intensity of eye blinks and can work as a neurological index.

2.1.1.2. Psychological responses. To measure the psychophysiological response perceived subjectively by the subject, psychological responses were collected via a self-report survey (refer to Fig. 2).

- ***MWL survey:*** The NASA-TLX assessment was performed to measure subjective MWL [32]. The NASA-TLX is a self-report assessment tool for evaluating the subject's workload. It consists of six dimensions (i.e., mental demand, physical demand, temporal demand, performance, effort, and frustration) and can be evaluated based on an 11-point Likert scale.
- ***DR survey:*** The Karolinska Sleepiness Scale (KSS), which evaluates alertness and sleepiness on a Likert 9-point scale, was used to measure subjective DR [5]. In addition, engagement and concentration, which are closely related to alertness, were measured together on a Likert 7-point scale.
- ***MFS survey:*** To evaluate subjective MFS, a survey to measure mental fatigue on a Likert 7-point scale was used. Affect Grid was used to quantitatively identify stress levels. Affect Grid is a tool developed to assess an individual's emotional state, and it was designed in the form of a coordinate to represent the two dimensions of emotion (i.e., pleasure and arousal) [33,34].
- ***VF survey:*** Because there are many types of VF, including ocular discomfort and visual disturbance, a survey designed to assess subjective VC comprises seven questions to check the degree of symptom [9]. Specifically, eye fatigue, eye pain, blurred vision, double vision, glare, eye dryness and eye itchiness were measured on a Likert 7-point scale [35].

2.1.2. Cognitive performance

This study sought to investigate the relationship between general office lighting, psychophysiological responses, and cognitive performance. Tests capable of measuring various cognitive abilities mainly used in the office were selected to examine various cognitive performances. Additionally, cognitive abilities were classified into two systems (i.e., primary and complex). Given the fact that most office work is done on computers in most modern offices, a computer-based test environment was configured for all the tests.

2.1.2.1. Primary cognitive performance test. In this study, tests were selected by referring to the six cognitive ability domains (i.e., attention, executive ability, memory, language, perceptual motor and social cognition) given in the Diagnostic and Statistical Manual of Mental Disorders published by the American Psychiatric Association [36] (refer to Fig. 3).

- ***Selective attention test:*** This test is designed to measure selective attention, which is the ability to focus only on necessary external stimuli and ignore other distracting factors [37]. Multiple objects with various shapes, color and movement appear randomly on the screen. From these objects, groups with the same shape, color and movement are present, and the subject was instructed to select and click on a unique object that does not belong to any group for 90 s (refer to Fig. 3 (A)).
- ***Task switching test***: This test measures a participant's task switching ability. Task switching refers to an individual's ability to quickly switch from one task to another and is important when handling multiple tasks simultaneously in an office [38]. Four

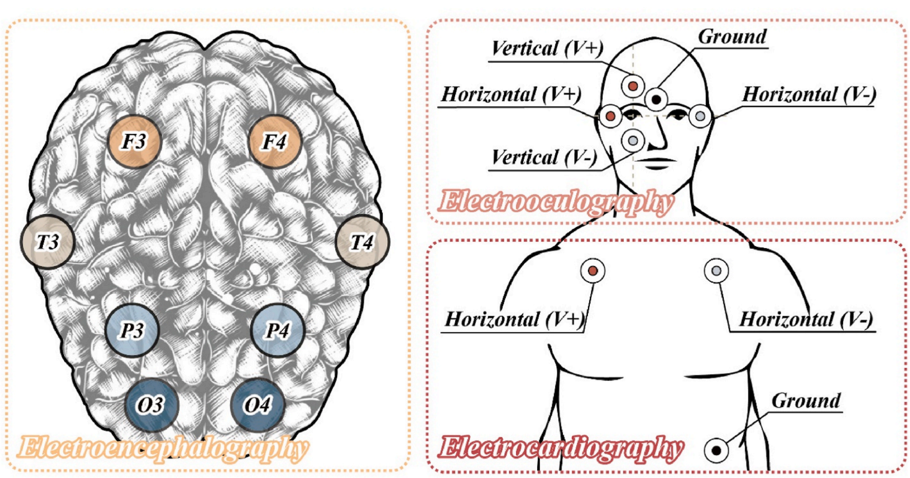

Fig. 1. Active electrode attachment locations for measuring physiological responses.

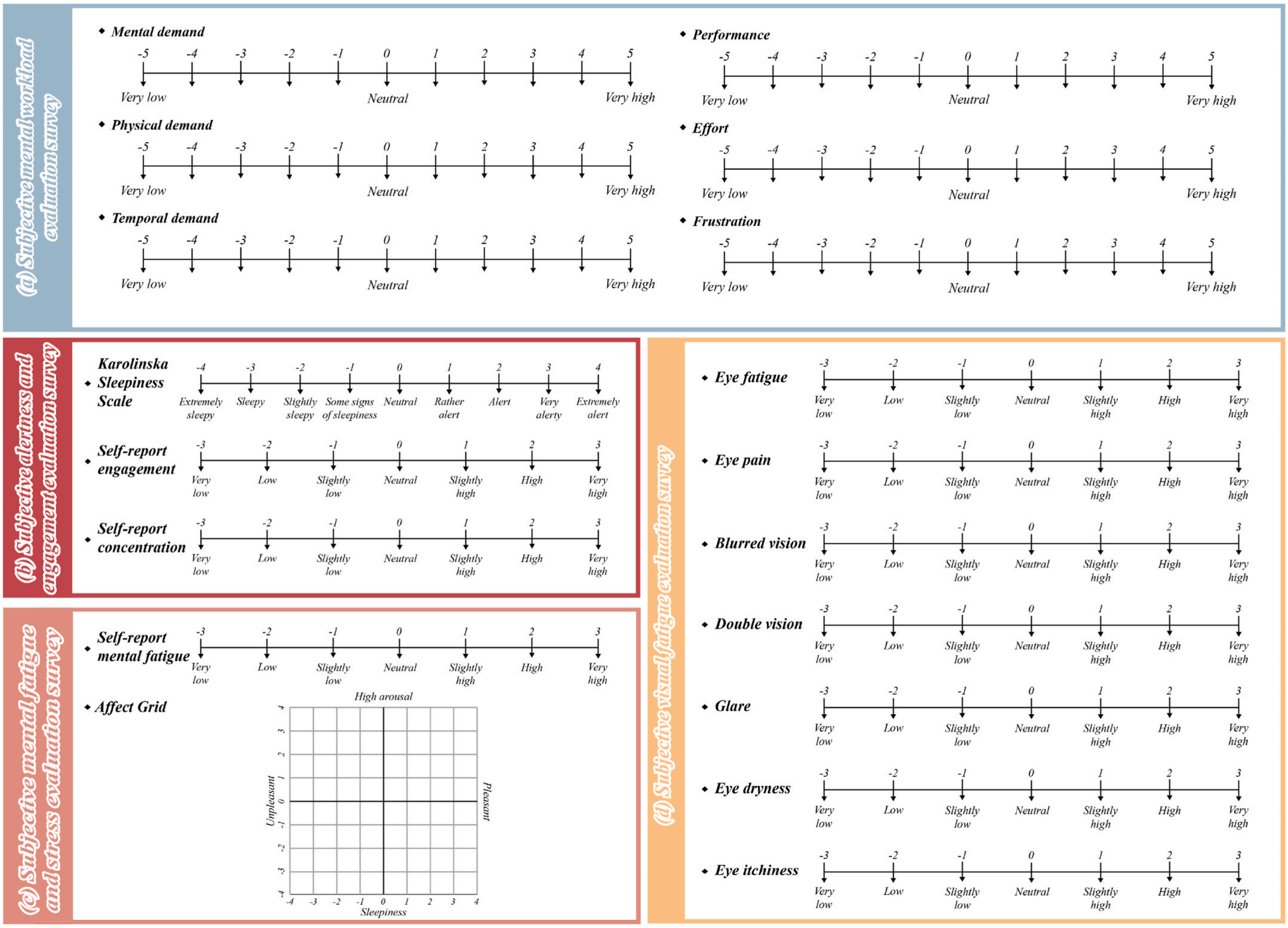

Fig. 2. Survey for measuring psychological responses.

columns appear on the screen, and cards that contain a combination of numbers and letters appear randomly in each column. There are a few criteria in the four columns: (i) whether the number is odd; (ii) whether the number is even; (iii) whether the letter is a consonant; (iv) whether the letter is a vowel. The subject was instructed to look at the cards that appear in random columns for 60 s, judge them according to the criteria for each column, and respond “yes” or “no” (refer to Fig. 3 (B)).

•***n-back test:*** This test measures the working memory’s ability to temporarily store and process information [39]. Cards with various shapes appear and disappear continuously on the screen. The subject is then asked to remember a series of cards for 60 s, determine whether the currently visible card matches the card three steps ahead, and then click if it matches (refer to Fig. 3 (C)).

•***Verbal fluency test:*** This test is used to measure verbal fluency. Verbal fluency is the ability to rapidly generate as many words as possible according to a specific category or starting letter. In particular, phonemic verbal fluency is measured by listing words that begin with a certain letter [40], and in this study, the subject was required to list words starting with a certain consonant. Questions were randomly assigned to each subject’s experiment to minimize the influence of factors such as the effect of learning or the degree of difficulty. Subjects were instructed to respond to 14 questions for 60 s. However, if any of the questions were difficult to answer or all the questions had already been answered, the subjects were allowed to list as many words as possible by answering additional questions during the remaining time (refer to Fig. 3 (D)).

•***Tracing test:*** Perceptual motor ability is the ability to perceive the environment through one’s senses, including vision, and interpret environmental cues to produce appropriate motor responses [41]. This test is used to evaluate the perceptual-motor coordination ability. A total of five radii with different lengths appear on the screen, and the subject must click on the given radius and draw a circle as accurately as possible with a mouse (refer to Fig. 3 (E)).

•***Reading the mind in the eyes test:*** Social cognition is the ability to understand and interpret other people’s actions, thoughts, feeling and intentions. The Reading the Mind in the Eyes Test developed by Professor Simon Baron-Cohen is used to evaluate the subject’s ability to infer an individual’s emotional state through only the eyes and expressions on the face around the eyes [42]. Four photos showing only the eyes and the expressions around the eyes, and four expression options that represent emotions for each photo were displayed on the screen, and the subject was instructed to select the emotion felt by the person in each photo within 30 s (refer to Fig. 3 (F)).

2.1.2.2. Complex cognitive performance test. Most of the work in an office requires the combined use of several primary cognitive abilities. With particular reference to basic work ability areas analyzed in various countries, including the United States, United Kingdom, Australia and South Korea, ‘creativity’, ‘reasoning’ and ‘comprehension’, the most commonly used complex cognitive abilities in the office, were selected [43]. The tests to measure each ability are as follows (refer to Fig. 4).

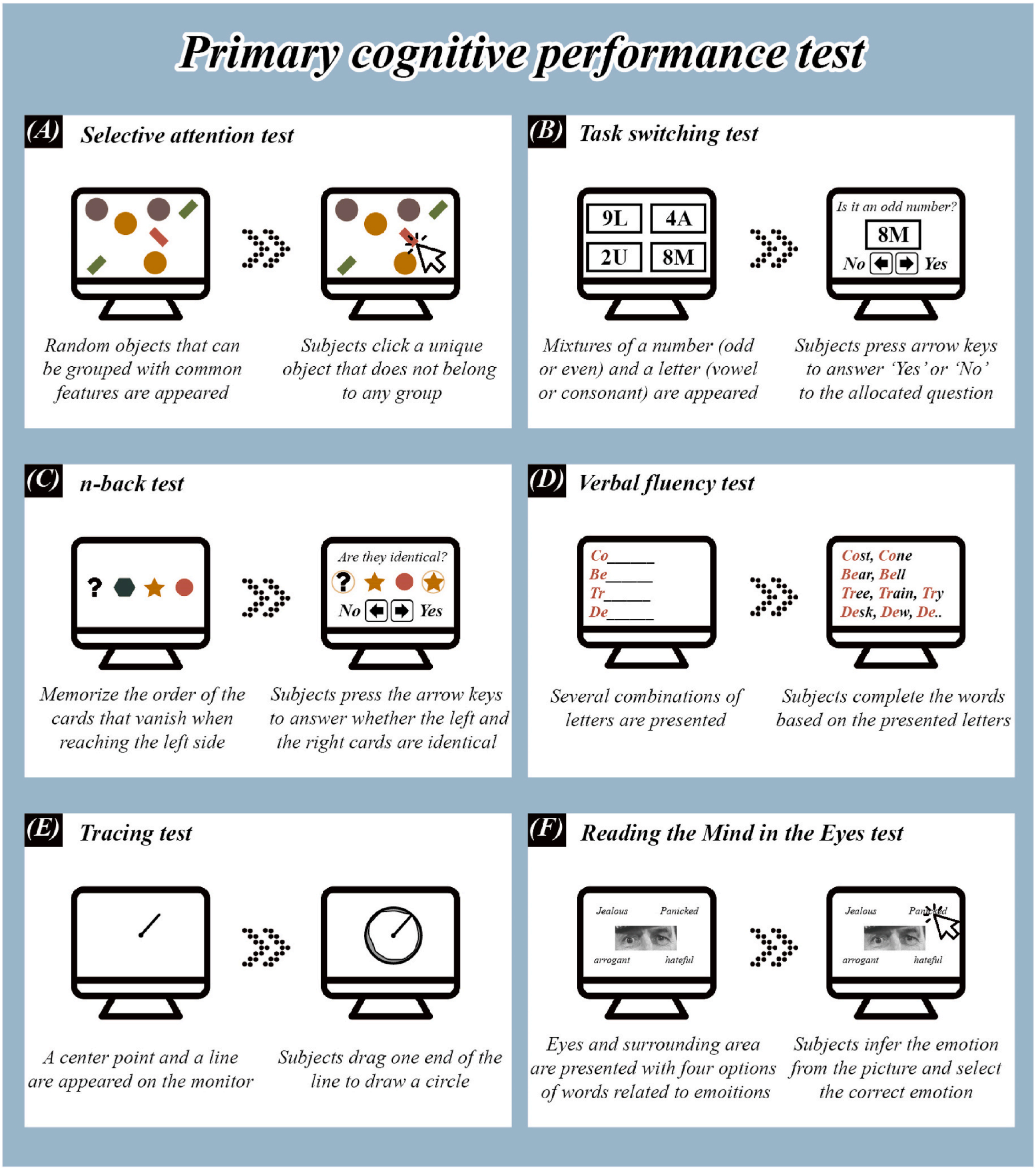

Fig. 3. Primary cognitive performance tests.

•***Alternative uses task (AUT) test:*** This test was developed by Guilford in 1967 and is mainly used to quantitatively evaluate creativity [44]. Everyday objects, such as paper clips or bricks, are displayed on the screen, and the subject is then asked to think of as many alternative uses for the object as possible for about 180 s (refer to Fig. 4 (A)).

•***Number pattern test:*** This test measures the reasoning ability to interpret numerical data and draw conclusions from datasets [45]. The screen presents a series of numbers with certain patterns. The subject is then instructed to predict and select the next number in each list based on the relationship between given numbers. A total of four questions with three levels of difficulty were randomly assigned to each of the nine experimental environments (refer to Fig. 4 (B)).

•***Reading comprehension test:*** This test is designed to measure a person's ability to read and accurately understand written texts [46]. Non-literary passages were extracted from the Korean language exam questions from Open Competitive Recruitment Test for Grade 9 (national positions). The passages were classified into short, medium and long passages based on the number of characters in each passage, and a test consisting of one short passage, one medium passage and one long passage was assigned to each experimental environment. The subject was required to read three passages per experiment and respond to multiple choice questions (refer to Fig. 4 (C)).

2.2. Data collection

2.2.1. Subject

The subjects recruited for this experiment consisted of a total of 16 healthy adults (i.e., 8 males and 8 females) aged 20–39 years (i.e., average age at 24.38 ± 2.45 years). This meant they were in a period of

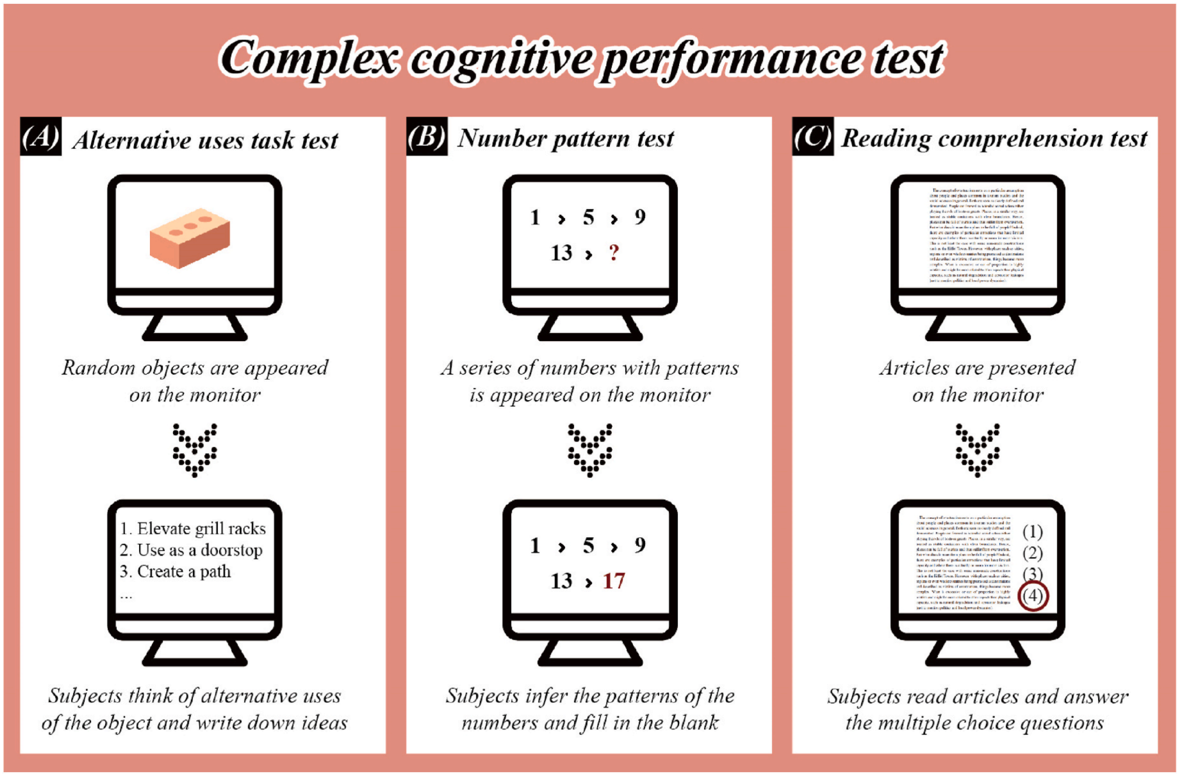

Fig. 4. Complex cognitive performance tests.

life between adolescence and middle age and their physical conditions, including vision, were relatively stable [47]. In addition, all subjects were college or graduate students who had no difficulty using computers or performing cognitive tests. Before conducting the experiment, all subjects confirmed that they had no history of chronic diseases or disorders such as color blindness or eye disease, high blood pressure, diabetes, stroke, or neurological disease. The average body mass index of the subjects was 21.86 ± 2.81 kg/m^2 which means none of them were obese or had low body weight [48]. In order to smoothly perform the cognitive test on the day of the experiment, they were asked to refrain from alcohol for 24 h before the experiment and to get enough sleep. In particular, caffeine intake was limited on the day of the experiment to prevent brain arousal.

2.2.2. Environment

An experiment was conducted in an artificial climate chamber to observe changes in psychophysiological responses and cognitive performances in various lighting environments. A total of 32 smart lighting emitting diode bulbs capable of controlling both CCT and illuminance within a certain range were uniformly installed on the ceiling of the artificial climate chamber. To implement a lighting environment similar to a typical office, three CCT values (i.e., 4,000K, 5,000K, and 6,500K) and three illuminance levels (i.e., 200lx, 500lx, and 800lx) were combined to create a total of nine lighting environments (refer to Fig. 5). Although there are no legal standards or recommendations for appropriate CCT for office lighting, the CCT range for daylight and warm white lighting mainly suggested to be used in general offices was selected [49–52]. Specifically, previous studies have revealed that CCT ranging from 4000 K to 5,000K was most preferred by occupants in offices and 6,500K was one of the most effective lightings for cognitive performance such as attention. The illuminance standard in South Korea indicates that recommended illuminance level in offices ranges from 150 to 1,500lx, specifically from 300 to 600lx in offices that usually use computers [53,54]. The experimental illuminance level was set at 500lx and ±300lx, keeping within these standards and ensuring to avoid

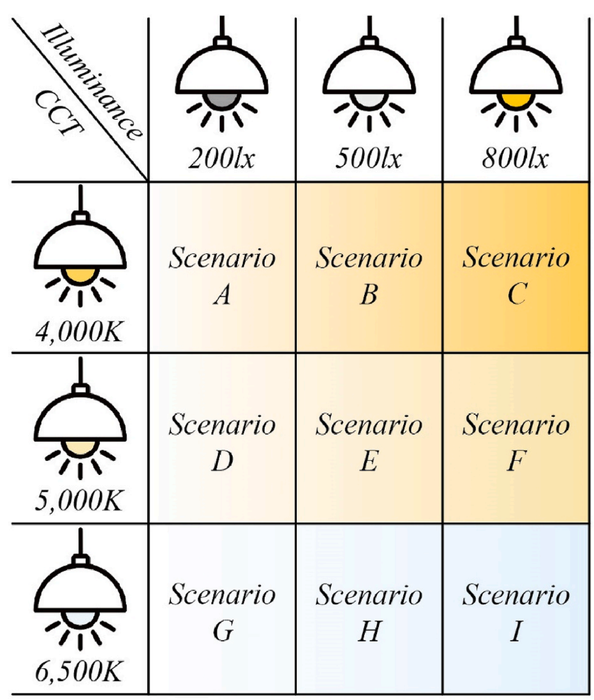

Fig. 5. Nine different lighting scenarios in experiments.

extreme lighting environments. In order to minimize the influence of environmental factors other than the lighting environment on the psychophysiological response and cognitive performance, the temperature ranged from 25 to 26 °C with a predicted mean vote of zero, and a relative humidity was maintained at 50 % [55].

2.2.3. Experiment

The overall process of the experiment in this study can be seen in Fig. 6. One subject participated in the experiment at a time, and the order of the nine lighting environments was randomly assigned to each subject to minimize the impact of learning effects that may occur while performing the same cognitive tests multiple times. Prior to the experiment, subjects were allowed to practice the test until they reached a certain score range so that they could fully understand the test. After confirming that the test score was stable, the subject wore EEG, EOG, ECG and eye tracking glasses according to the instructions. Then, the following experimental sequence was repeated a total of nine times, once for each lighting environment. Firstly, while the lighting environment was created, subjects closed their eyes and waited to avoid being stimulated when the lighting environment changed. Once the lighting environment was set, the subjects opened their eyes and performed attention, executive ability, memory, language, perceptual motor, and social cognition tests in sequence to evaluate primary cognitive performance. Next, the subjects performed creativity, reasoning, and comprehension tests in sequence to measure complex cognitive performance. After performing all the tests, the subjects responded to a survey to generate self-report responses to MWL, DR, MFS and VF. After completing all the tests and survey responses, they turned their heads away from the monitor and took a rest while looking at a distant object. Afterwards, the subjects closed their eyes and rested, and after a rest period of about 10 min, the same process was repeated by creating the next lighting environment. Each experiment took approximately 20 min, and all the experiments were performed over a total of approximately 4 h. The experimental process was approved after deliberation on ethical and scientific validity by the Institutional Review Board at Yonsei University [7001988-202311-HR-2089-02].

2.3. Data analysis

2.3.1. Data preprocess

The following data processing procedures were performed to convert the raw data of physiological responses collected through EEG, ECG and eye tracking glasses into objective indices to be measured in this study. First, processing for EEG signals was done using 'AcqKnowledge' software provided by Biopac Systems and scipy.signal library in Python [56]. The raw data of EEG includes various factors, such as eye or muscle movement, and heartbeat. Meanwhile, comb band-pass filters were used to remove signals of unnecessary frequencies included in brain waves such as artifacts, and artifacts caused by eye movement were eliminated using measured EOG data. In addition, the brain wave in the time domain was converted into four frequency bands (delta, theta, alpha and beta wave) for each frontal, temporal, parietal and occipital lobe via the power spectral density [57]. As in EEG, outliers in ECG were removed using comb band-pass filters through the AcqKnowledge software, and MHR, SDNN and RMSSD were extracted using the HeartPy library in Python. Psychological responses were collected through a survey, and all items were quantified using a Likert scale. For the Affect Grid, raw data was recorded in the form of a coordinate. Among the responses in the form of coordinates, x was converted into a scale of 'pleasure-displeasure', while y was converted into that of 'arousal-sleepiness'.

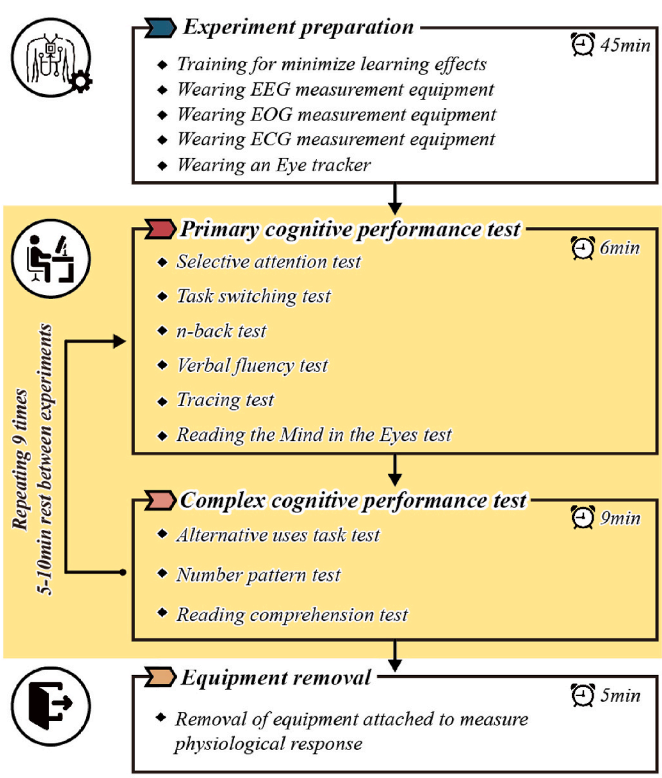

Fig. 6. Process of experiment.

Meanwhile, the number of correct answers and the number questions answered were recorded in tests designed to measure attention, executive ability, memory, and social cognition. The accuracy of the verbal fluency test was calculated by determining that the case where there was at least one response appropriate to the standard for each of the 14 given questions was judged to be correct, and the response time was calculated based on the number of responses written for 60 s. In the tracing test, the average accuracy derived by itself was recorded as accuracy, and the response time was derived by calculating the average of the time to draw all five circles. Among the complex cognitive performances, creativity was given scores based on general AUT standards. The evaluation criteria of AUT are as follows: (i) fluency is evaluated in terms of the ability to develop many ideas; (ii) flexibility in terms of the ability to present ideas in various categories; (iii) originality in terms of the ability to produce unusual ideas; (iv) elaboration in terms of the ability to create ideals in detail. Points are assigned to each idea with a detailed criteria set, and the sum of the points given to the four criteria then calculated as the total score of AUT. The reaction time was calculated based on the number of responses over 180 s. Among the complex cognitive performances, there were four types of reasoning with three levels of difficulty. The accuracy was calculated based on a total score of 11 points, with 2 points given to the lowest level questions, 3 points to one question from the second level, and 4 points to one question from the third level. Lastly, the accuracy of comprehension was calculated based on a total score of 12 points, with 2, 4 and 6 points assigned by length of the passages. The accuracy and response times were used to derive indices representing cognitive performance [58]. In addition, because the scale of cognitive performance varies depending on the characteristics of the test, T scores were used for standardization. The T score, which was converted to a normal distribution with a mean of 50 and a standard deviation of 10 as a raw score was converted into a standardized score, was set as an index for the final cognitive performance.

2.3.2. Integrated indices derivation using canonical correlation analysis and principal components analysis

In this study, a wide variety of physiological and psychological responses were collected. Therefore, in order to more effectively investigate the relationship between lighting, psychophysiological responses and cognitive performance, attempts were made to derive objective and subjective integration indices for each psychophysiological response based on physiological and psychological responses. First, there was a need to identify and classify to which of the four types of psychophysiological responses the collected and preprocessed physiological responses correspond. Therefore, in this study, the physiological responses corresponding to each psychophysiological response were selected via canonical correlation analysis (CCA). The CCA is a statistical method exploring the relationship between two sets of variables. Specifically, the pair that maximizes the correlation between two linear combinations of variables in a set was found, and then the linear combination with the highest correlation between the two groups of variables was searched for [59,60]. Meanwhile, CCA is also a process of understanding and interpreting the relationship between two sets of variables. In this study, because multiple psychological responses exist for each psychophysiological response, CCA, which analyzes the relationship between a set of variables rather than a single variable, was selected as a methodology. In this study, one CCA dataset consisted of overall physiological responses, and another CCA dataset comprised survey responses, which were the psychological responses of each psychophysiological response. CCA was performed on two datasets for each psychophysiological response, and the physiological responses were filtered based on the canonical absolute weight of the physiological responses.

Second, data duplication and multicollinearity problems may arise when physiological responses and psychological responses are considered in a separate manner. Accordingly, various indices were simplified into integrated indicators to effectively perform the analysis. In addition, because physiological responses and psychological responses are very different in nature, and their measurement methods also vary widely, all responses were not integrated into one. Instead, they were derived separately as objective and subjective indices, respectively [9]. The physiological and psychological indices of each psychophysiological response were standardized, the scale was adjusted, and principal component analysis (PCA) was performed to develop objective and subjective integrated indicators [61]. PCA is a method of reducing the dimensionality of data while preserving the variance of the data as much as possible. In addition, the use of PCA can make it possible to resolve the problem of multicollinearity in regression analysis due to a high correlation between independent variables. PCA involves capturing the main components of data and rotating the data when the rotation matrix is used. In this study, the Varimax rotation method, one of the methods for optimally rotating the principal component loading matrix in the PCA results, was used. The rotated principal component loading matrix can reveal the structure of the data more clearly, and in this study, an integrated index was developed by setting the first principal component loading of the rotated component matrix as the weight of each index [62] (refer to Eq. (1)). In this process, one of the principal components can be selected by examining factors such as a variable loading, and positive or a negative relationship between variables, and the variables can be removed based on the criteria. However, since the first principal component explains the largest variance in the data, it is likely to contain important information in the data. The first principal component loading was used because it is not possible to quantitatively determine the degree of correlation between each index and psychophysiological response. In addition, since the positive or negative relationship between physiological response and psychophysiological response may not be consistently revealed, the loading is used as it minimizes the risk of data loss. However, because the psychological response clearly has a positive relationship with the psychophysiological response, the index is excluded when the loading is negative.

$$\textit{Integrated index} = \sum_{i=1}^{k} L_1 \bullet X_1 + L_2 \bullet X_2 + \cdots + L_k \bullet X_k \tag{1}$$

Where, L stands for the loading of principal component; X stands for physiological or psychological responses.

2.3.3. Statistical analysis

The relationships between general office lighting (i.e., CCT and illuminance), psychophysiological responses (i.e., MWL, DR, MFS and VF) and cognitive performance (i.e., primary and complex) were investigated using statistical methods; (i) mixed linear model (MLM), (ii) repeated measures two-way analysis of variance (ANOVA) and (iii) multiple regression analysis (MRA).

First of all, MLM and repeated measures two-way ANOVA were used to investigate the general office lighting impact on psychophysiological responses. MLM is a statistical model, a type of linear regression model that has both fixed effects and random effects [63,64]. The fixed effects correspond to independent variables as experimental conditions such as general office lighting, while the random effects can take individual differences or variance in repeated measures into account. MLM is an effective method when repeated measures are made on an experimental unit, or if the hierarchical structure of data is complex. There are three different fixed effects; (i) CCT only, (ii) illuminance only and (iii) CCT and illuminance together. Random effects are all set as subject identification and dependent variables were set as each psychological response and cognitive performance. MLMs that have a single fixed effect can provide statistical results by CCT and illuminance respectively, which can be easily compared and analyzed. MLM with two fixed effects can also consider the interaction between CCT and illuminance. For supplementary analysis, repeated measures two-way ANOVA was also used. It is a statistical test to evaluate the influence of two independent variables (i.e., CCT and illuminance) on dependent variables, where the same subjects are measured under different conditions. This method accounts for the correlations between measurements taken from the same subjects, enhancing the analysis's sensitivity to detect differences.

Secondly, MLM and MRA were used to investigate the mutual relationships between psychophysiological responses and cognitive performances. MRA is a statistical technique for modeling the relationship between a dependent variable and two or more independent variables (refer to Eq. (2)) [65,66]. The impact of multiple independent variables on the dependent variable can be evaluated simultaneously, and the partial effect of each independent variable on the dependent variable can be estimated. MRA is an advantageous method for understanding complex relationships within data. As MLM and MRA have strengths suited for different situations and data structures, they can clarify the comprehensive relationships of general office lighting, psychophysiological response, and cognitive performance from different angles. For example, when the impact of general office lighting on cognitive performance was investigated, the results of the MLM were mainly analyzed. Although CCT and illuminance are variables to be applied equally to all subjects, cognitive performance may vary depending on each subject's abilities. However, unlike cognitive performance, psychophysiological responses may not have a large individual difference due to human physiological and psychological response. And if the independent variable is not lighting, it may be difficult to consider it as a fixed effect. Thus, MRA was also done for a more in-depth analysis, focusing on the impact of psychophysiological responses and cognitive performance rather than individual differences. In the analysis where cognitive performance impact was investigated, all types of cognitive performance impacts were set as fixed effects or independent variables. However, in the analysis where psychophysiological responses was investigated, MWL, DR, MFS and VF were separately set as fixed effects or independent variables. For example, objective integrated index and subjective integrated index of MWL were set as fixed effect together. Objective and subjective integrated indices of MWL, DR, MFS and VF could not be all set as fixed effect together, as the variance inflation factor was more than 10. All the assumptions for statistical analysis (i.e., Shapiro-Wilk test for normality, Durbin-Watson for independence and Breusch-Pagan test for homogeneity of variance, etc) were checked before implementation. Although every variables satisfied the assumptions for statistical analysis, bootstrapping with 5000 iterations was applied to reduce the uncertainty of the analysis.

$$Y_{ij} = \beta_0 + \beta_1 X_{ij} + u_j + \epsilon_{ij} \tag{2}$$

Where, Y_{ij} stands for the ith observation of jth group of dependent variable Y; β_0 stands for the intercept of fixed effect; β_1 stands for the coefficient of fixed effect; X_{ij} stands for the ith observation of jth group of independent variable X; u_j stands for the random effect of jth group; and

e_{ij} stands for residual term.

3. Results

3.1. Impact of general office lighting on cognitive performance and psychophysiological responses

3.1.1. General office lighting impact on cognitive performance

Table 1 summarizes the impact of CCT and illuminance on cognitive performance via MLM. The fixed effects were CCT and illuminance respectively while the random effect was the identification of the subject. As it is difficult to decide one lighting scenario as baseline lighting, illuminance and CCT were separately set as fixed effect to compare the impact by illuminance and CCT. Firstly, illuminance has a positive effect on attention when the CCT is the same, while CCT has positive effects on executive ability and memory when the illuminance is the same. These results are consistent with findings revealed by Fu et al. (2023), which showed that the higher the illuminance, the higher the attention and the higher the CCT, the higher the memory [67]. However, according to their research, the lower the illuminance leads to the higher memory, and the higher CCT yields higher attention, but the results of this study did not show these trends. In the case of the remaining primary cognitive performance, all p-values were 0.05 or more, indicating that it was not affected by lighting. Additionally, complex cognitive performance did not show any statistical significance with illuminance or CCT. Secondly, even when illuminance and CCT were set as independent variables together, the same results were shown as when each was set as an independent variable. Lastly, there was group variance for significant models. In other words, there are individual differences in cognitive performance, which suggests that the impact of individual's cognitive performance may not be consistent depending on lighting. Table 2 shows the results of repeated measured two-way ANOVA, specifically the impact of general lighting (i.e., CCT and illuminance) on cognitive performance. The results were similar to that from MLM, but there were two more findings. The illuminance and CCT interaction term was found to have significantly positive impact of perceptual motor and social cognition. This indicates that the combined effect of illuminance and CCT on the dependent variables is more than simply adding the individual effects of the two factors. The effect of illuminance may vary depending on the level of CCT, and vice versa for perceptual motor and social cognition.

3.1.2. General office lighting impact on psychophysiological response

Tables 1 and 2 show the impact of general lighting on psychophysiological responses through MLM and repeated measures two-way ANOVA. The results of the analysis through MLM where illuminance or CCT was set as fixed effect revealed that the p -value was 0.05 or more for all psychophysiological responses, indicating that the impact of lighting on psychophysiological responses has no statistical significance. Even when the impact of lighting on psychophysiological responses was investigated through repeated measures two-way ANOVA, all p-values were above the reference value and had no statistical significance. However, in the MLM where illuminance and CCT were set as fixed effects together, illuminance had a positive effect on objective DR and CCT had a significantly positive effect on subjective CCT. These were the only findings that were significant when investigating general office lighting impact on psychophysiological responses. This finding can be contradictory to some of the previous studies that insisted MWL, DR, MFS and

Table 1
Office lighting impact on cognitive performance and psychophysiological response analyzed by mixed linear model.

Dependent variable		Parameters	Illuminance	CCT	Illuminance and CCT	
					Illuminance	CCT
Cognitive performance	Attention	Coefficient (p-value)	0.068 (0.022*)	0.038 (0.197)	0.068 (0.021*)	0.038 (0.190)
		Group variance	0.016 (0.049)	0.016 (0.048)	0.016 (0.049)	
	Executive ability	Coefficient (p-value)	0.033 (0.182)	0.096 (0.000*)	0.033 (0.157)	0.096 (0.000*)
		Group variance	0.025 (0.084)	0.025 (0.088)	0.025 (0.089)	
	Memory	Coefficient (p-value)	0.044 (0.152)	0.149 (0.000*)	0.044 (0.112)	0.149 (0.000*)
		Group variance	0.021 (0.061)	0.021 (0.067)	0.021 (0.067)	
	Language	Coefficient (p-value)	0.012 (0.660)	−0.013 (0.633)	0.012 (0.660)	−0.013 (0.634)
		Group variance	0.009 (0.031)	0.009 (0.031)	0.009 (0.031)	
	Perceptual motor	Coefficient (p-value)	−0.178 (0.182)	0.200 (0.129)	−0.178 (0.180)	0.200 (0.128)
		Group variance	0.366 (0.245)	0.366 (0.245)	0.366 (0.246)	
	Social cognition	Coefficient (p-value)	0.019 (0.630)	0.022 (0.578)	0.019 (0.631)	0.022 (0.579)
		Group variance	0.001 (0.010)	0.001 (0.010)	0.001 (0.010)	
	Creativity	Coefficient (p-value)	−0.009 (0.631)	0.004 (0.841)	−0.000 (0.968)	−0.003 (0.787)
		Group variance	0.012 (0.055)	0.012 (0.055)	0.004 (0.029)	
	Reasoning	Coefficient (p-value)	−0.054 (0.547)	−0.161 (0.066)	−0.056 (0.542)	−0.161 (0.075)
		Group variance	0.063 (0.075)	0.064 (0.076)	0.067 (0.077)	
	Comprehension	Coefficient (p-value)	−0.051 (0.162)	0.019 (0.613)	−0.051 (0.164)	0.019 (0.612)
		Group variance	0.011 (0.031)	0.011 (0.031)	0.011 (0.031)	
Psychophysiolo- gical response	Objective MWL	Coefficient (p-value)	0.036 (0.358)	0.059 (0.129)	0.036 (0.356)	0.059 (0.129)
		Group variance	0.027 (0.063)	0.027 (0.063)	0.027 (0.063)	
	Subjective MWL	Coefficient (p-value)	0.117 (0.360)	−0.035 (0.785)	0.117 (0.362)	−0.035 (0.786)
		Group variance	0.110 (0.095)	0.110 (0.095)	0.110 (0.095)	
	Objective DR	Coefficient (p-value)	0.036 (0.682)	0.020 (0.823)	0.165 (0.035*)	0.001 (0.985)
		Group variance	0.050 (0.115)	0.050 (0.116)	0.045 (0.208)	
	Subjective DR	Coefficient (p-value)	−0.025 (0.448)	0.006 (0.865)	−0.37 (0.356)	0.083 (0.036)
		Group variance	0.036 (0.092)	0.036 (0.092)	0.035 (0.078)	
	Objective MFS	Coefficient (p-value)	0.010 (0.804)	−0.024 (0.534)	−0.024 (0.174)	0.010 (0.579)
		Group variance	0.021 (0.050)	0.021 (0.050)	0.002 (0.011)	
	Subjective MFS	Coefficient (p-value)	0.012 (0.725)	0.018 (0.603)	0.012 (0.725)	0.018 (0.603)
		Group variance	0.002 (0.013)	0.002 (0.013)	0.003 (0.014)	
	Objective VF	Coefficient (p-value)	0.008 (0.786)	−0.014 (0.631)	−0.006 (0.688)	0.005 (0.738)
		Group variance	0.009 (0.029)	0.009 (0.029)	0.001 (0.010)	
	Subjective VF	Coefficient (p-value)	−0.005 (0.943)	−0.013 (0.861)	0.011 (0.885)	0.037 (0.633)
		Group variance	0.135 (0.160)	0.135 (0.160)	0.104 (0.123)	

Note: CCT for correlated color temperature; MWL for mental workload; DR for drowsiness; MFS for mental fatigue stress; VF for visual fatigue; * for statistically significant p-value; Group variance value for coefficient (standard error).

Table 2
Office lighting impact on cognitive performance and psychophysiological response analyzed by repeated measures two-way ANOVA.

Dependent variables		Parameter	F-value	p-value
Cognitive performance	Attention	CCT	4.961	0.013*
		Illuminance	1.428	0.256
		CCT*Illuminance	0.951	0.441
	Executive ability	CCT	5.898	0.007*
		Illuminance	1.972	0.157
		CCT*Illuminance	0.130	0.971
	Memory	CCT	12.946	0.000*
		Illuminance	1.400	0.262
		CCT*Illuminance	1.372	0.254
	Language	CCT	0.087	0.917
		Illuminance	0.856	0.435
		CCT*Illuminance	1.156	0.339
	Perceptual motor	CCT	0.700	0.504
		Illuminance	2.731	0.081
		CCT*Illuminance	3.364	0.015*
	Social cognition	CCT	1.702	0.199
		Illuminance	1.065	0.357
		CCT*Illuminance	2.800	0.034*
	Creativity	CCT	0.662	0.523
		Illuminance	1.101	0.346
		CCT*Illuminance	0.515	0.725
	Reasoning	CCT	0.935	0.404
		Illuminance	0.266	0.769
		CCT*Illuminance	0.939	0.448
	Comprehension	CCT	1.039	0.366
		Illuminance	2.605	0.366
		CCT*Illuminance	0.887	0.478
Psychophys- iological responses	Objective MWL	CCT	2.306	0.117
		Illuminance	0.829	0.446
		CCT*Illuminance	0.682	0.607
	Subjective MWL	CCT	0.574	0.569
		Illuminance	0.586	0.563
		CCT*Illuminance	1.347	0.263
Psychophys- iological	Objective DR	CCT	0.719	0.495
		Illuminance	2.439	0.104
		CCT*Illuminance	0.520	0.721
	Subjective DR	CCT	2.911	0.070
		Illuminance	0.832	0.445
		CCT*Illuminance	2.082	0.094
	Objective MFS	CCT	0.318	0.730
		Illuminance	1.361	0.272
		CCT*Illuminance	0.907	0.466
	Subjective MFS	CCT	0.119	0.889
		Illuminance	0.645	0.532
		CCT*Illuminance	1.356	0.260
	Objective VF	CCT	0.093	0.912
		Illuminance	0.531	0.593
		CCT*Illuminance	0.182	0.947
	Subjective VF	CCT	0.541	0.588
		Illuminance	1.833	0.177
		CCT*Illuminance	0.966	0.433

Note: CCT for correlated color temperature; * for statistically significant *p*-value; MWL for mental workload; DR for drowsiness; MFS for mental fatigue stress; VF for visual fatigue.

VF can be affected by lightings [11,19,21]. However, there were also existing studies that revealed different lightings do not have significant impact on psychophysiological responses [23]. Regardless of whether individual variance was considered, nine types of lighting settings created in the experiment of this study did not have a consistent impact on the subject's psychophysiological responses in most cases.

Figs. 7 and 8 show subjects' objective and subjective psychophysiological responses under nine types of lighting settings. MWL and DR were highest in a lighting environment with a CCT value of 4,000K and an illuminance level of 500lx, and MFS was highest when CCT was 5,000K, and illuminance was 800lx. On the other hand, VF was highest when CCT was 6,500K, and illuminance was 800lx but showed a very slight difference from other environments. As shown in Fig. 7, the objective and subjective integrated indices of MWL, MFS and VF do not show a consistent trend according to CCT or illuminance. The investigation of the mean value of each psychophysiological response according to lighting found that the standard deviation was 0.04 or less, showing a very small difference depending on the environment.

3.2. Impact of mutual influence between psychophysiological response and cognitive performance

3.2.1. Psychophysiological responses impact on cognitive performance

Table 3 shows the results of MLM and MRA investigating the impact of psychophysiological responses on cognitive performance. Firstly, MWL affects attention, executive ability and memory among primary cognitive performances and shows statistical significance with creativity among complex cognitive performances. Specifically, attention showed statistical significance with the objective integrated index of MWL, and the remaining cognitive performance was significantly affected by the subjective integrated index of MWL. Meanwhile, the objective integrated index showed a positive correlation with cognitive performance, whereas the subjective integrated index showed a negative correlation. Furthermore, MRA results showed that objective and subjective MWL has a significant effect on attention, executive ability, memory, perceptual motor, creativity and comprehension. Attention, perceptual motor, creativity and comprehension showed statistical significance with the objective integrated index of MWL. Executive ability and memory showed statistical significance with both the objective and subjective indices of MWL. All except for perceptual motor showed a positive correlation among those that showed statistical significance with the objective MWL. A positive correlation between MWL and cognitive performances such as creativity has been also revealed by previous study [68].

Secondly, the impact of DR on cognitive performance with MLM found that DR had an impact on executive ability among primary cognitive performances but did not show statistical significance among complex cognitive performances. Moreover, the MRA results show that primary cognitive performances affected by DR were attention, executive ability, and memory, and among the complex cognitive performances, creativity and comprehension showed statistical significance. All cognitive performances showed statistical significance with the objective integrated index of DR, and all showed a positive correlation. In addition, attention, executive ability, and memory showed statistical significance with the subjective integrated index, and all showed a negative correlation.

Thirdly, impact of MFS with MLM found that, among primary cognitive performances, MFS had an impact on attention, while none showed statistical significance among the complex cognitive performances. The attention showed statistical significance and a positive correlation with the objective integrated index. Also, the MRA results with the objective and subjective integrated indices of MFS as independent variables and each cognitive performance as dependent variables are as follows. Among the primary cognitive performances, those affected by MFS were attention, executive ability, memory, and language, and among the complex cognitive performances, creativity showed statistical significance. All cognitive performances showed statistical significance with the objective integrated index of MFS, and all showed a positive correlation. The memory showed statistical significance and a positive correlation with the subjective integrated index as well.

Finally, the impact of VF with MLM found that VF had an impact on attention among primary cognitive performances, and creativity among the complex cognitive performances. The attention showed statistical significance and a positive correlation with the objective integrated index of VF, while creativity showed a negative correlation with the subjective integrated index of VF. Moreover, the MRA results with the objective integrated index and subjective integrated index of VF as independent variables and each cognitive performance as dependent variables are as follows. Among the primary cognitive performances,

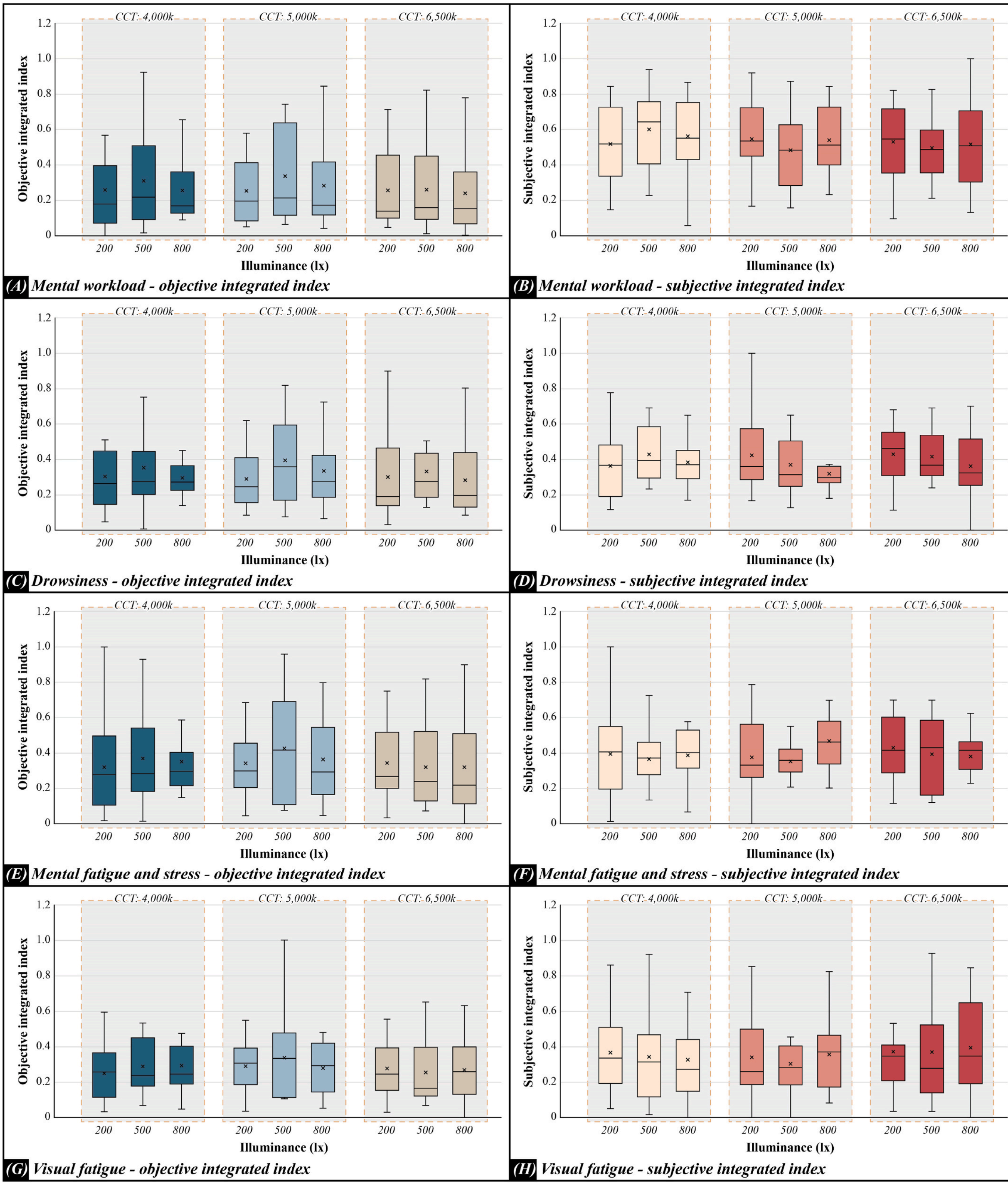

Fig. 7. Psychophysiological responses under different office lightings.

those affected by VF were attention, executive ability, memory, and language, and among the complex cognitive performances, creativity showed statistical significance. The attention, executive ability, and memory showed statistical significance with the objective integrated index, and all showed a positive correlation. In addition, the subjective integrated index showed statistical significance with executive ability, memory, language, and creativity, and all showed a negative correlation. The finding that VF can affect cognitive performance has been also suggested by Akagi et al. (2022) who investigated subjects' brain activity after VF has appeared [69].

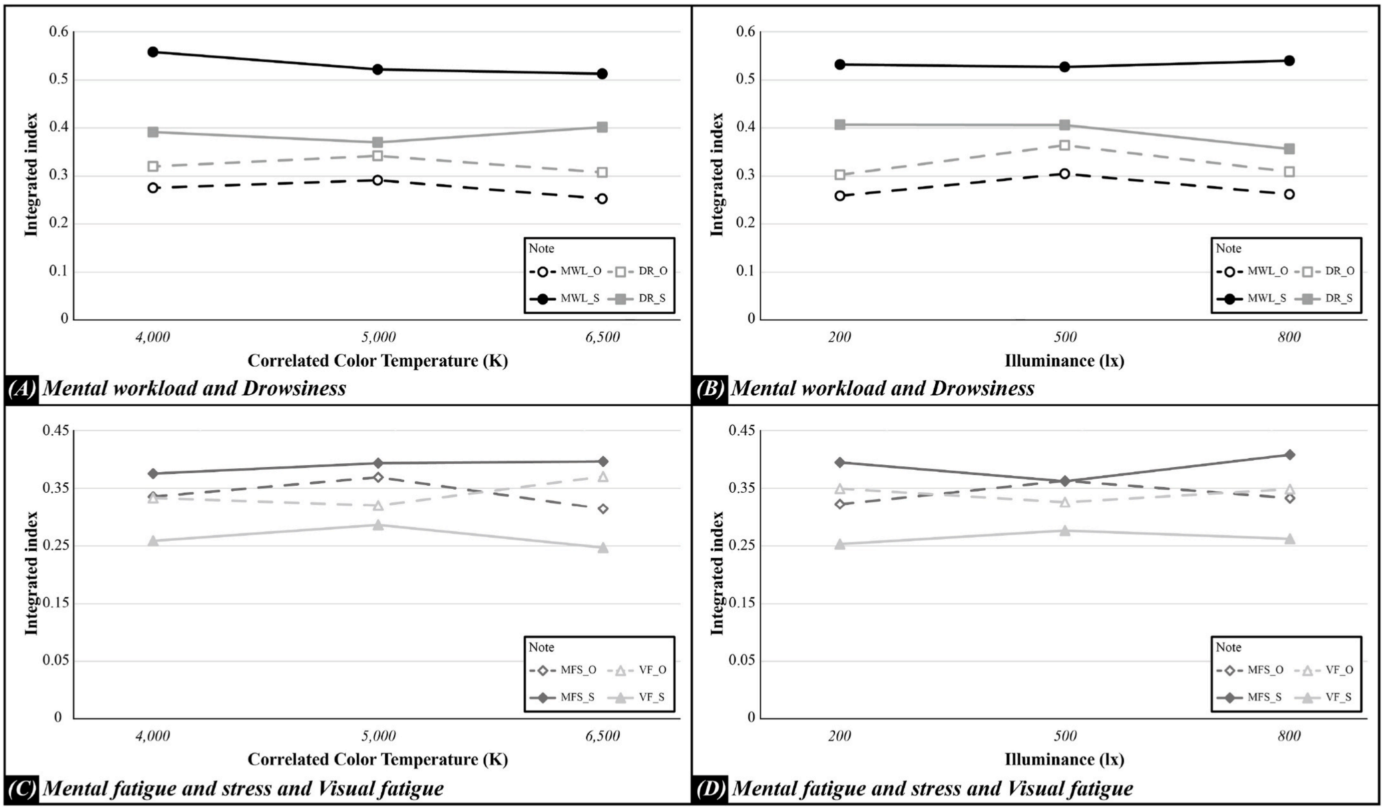

Fig. 8. Psychophysiological response changes under different correlated color temperature and illuminance.

3.2.2. *Cognitive performance impact on psychophysiological responses*

Tables 4 and 5 shows the results of MLM and MRA investigating the impact of cognitive performance on psychophysiological response. In MLM, cognitive performances were set as fixed effects, and their impact on psychophysiological response was investigated. As a result, the psychophysiological responses in which cognitive performances were influential as independent variables were MWL, DR and VF. It seems that the objective integrated index of MWL is statistically significantly affected by attention, while the subjective integrated index of MWL is statistically significantly affected by memory. The objective integrated index showed a positive correlation, and the subjective integrated index showed a negative correlation depending on cognitive performance. Subjective DR is significantly affected by executive ability and it showed a negative correlation. Attention is a statistically significant independent variable that affects objective VF and it showed positive correlation.

In MRA, the following results were obtained. First, all psychophysiological responses except for the subjective integrated index of MFS were affected by cognitive performance. Also, the objective integrated index of MWL had statistical significance in its correlation with executive ability and creativity and was found to have positive correlations, respectively. The subjective integrated index of MWL had a significant impact on executive ability, memory, and social cognition, and all were found to have a negative correlation. The objective integrated index of DR had statistical significance in its correlation with executive ability, creativity, and reasoning, and they were all found to have a positive correlation. The subjective integrated index of DR had a significant impact on executive ability and was found to have a negative correlation. The objective integrated index of MFS had statistical significance in its correlation with attention, memory and language, and they were found to have a positive correlation. Finally, the objective integrated index of VF had a significant impact on attention and executive ability, and both were found to have a positive correlation. The subjective integrated index of VF had a significant impact on executive ability, memory, language, creativity and reasoning, and all were found to have a negative correlation.

4. Discussion

4.1. *Relationships between general office lighting, psychophysiological response, and cognitive performance*

4.1.1. *Research question 1: How does general office lighting impact psychophysiological responses and cognitive performance?*

In this study, a subject's computer-based cognitive performance and psychophysiological response were measured and the relationships with the ranges of lighting (i.e., CCT and illuminance) generally used in a modern office were investigated. The results revealed that there is a difference in cognitive performance depending on lighting even in a non-extreme lighting environment and a situation in which computer-based tasks are carried out. The lighting had an impact on all primary cognitive performances except for language, and all were found to have a positive correlation with CCT or illuminance. That is, at least in the range of CCT (i.e., 4000–6,500K) and the level of illuminance (i.e., 200–800lx), the cooler and brighter the lighting, the higher the primary cognitive performance. In other words, lighting similar to daylight can be optimal for the cognitive performance of the occupants in an office. However, while lighting had an impact on primary cognitive performance, there was no statistically significant impact of lighting on complex cognitive performance with a combined action of primary cognitive ability. This suggests that although the lighting environment can have an impact on primary cognitive performance, which is relatively intuitive, its impact may not be consistent in complex cognitive performance that requires a high order mental process. Moreover, a case in which there was statistical significance in MLM was found to have no statistical significance in MRA. This suggests that individual differences should be considered when investigating the impact on cognitive performance and that lighting has an impact, which is not generalized across individuals. Furthermore, in this study, lighting had no

Table 3
Impact of psychophysiological response on cognitive performance.

Dependent variable	Parameter	Mixed linear model				Multiple regression model							
		Coefficient (*p*-value)				*p*-value				Standardized coefficient (*p*-value)			
		MWL	DR	MFS	VF	MWL	DR	MFS	VF	MWL	DR	MFS	VF
Attention	Objective index	0.191 (0.009*)	0.131 (0.087)	0.145 (0.025*)	0.201 (0.022*)	0.011*	0.007*	0.002*	0.001*	0.195 (0.001*)	0.156 (0.012*)	0.234 (0.000*)	0.280 (0.001*)
	Subjective index	−0.033 (0.681)	−0.120 (0.179)	0.100 (0.186)	0.062 (0.516)					−0.070 (0.324)	−0.239 (0.031*)	0.079 (0.304)	−0.099 (0.155)
	Group variance	0.015	0.014	0.014	0.015								
Executive ability	Objective index	0.084 (0.304)	0.095 (0.254)	0.074 (0.299)	0.108 (0.257)	0.000*	0.000*	0.010*	0.000*	0.208 (0.001*)	0.227 (0.012*)	0.240 (0.004*)	0.297 (0.005*)
	Subjective index	−0.192 (0.035*)	−0.212 (0.028*)	0.117 (0.150)	0.003 (0.982)					−0.425 (0.000*)	−0.643 (0.000*)	0.177 (0.108)	−0.292 (0.002*)
	Group variance	0.031	0.032	0.036	0.037								
Memory	Objective index	0.031 (0.689)	−0.011 (0.887)	0.032 (0.636)	0.066 (0.457)	0.000*	0.001*	0.000*	0.000*	0.240 (0.000*)	0.230 (0.001*)	0.266 (0.000*)	0.268 (0.004*)
	Subjective index	−0.204 (0.011*)	−0.065 (0.468)	0.139 (0.064)	−0.170 (0.060)					−0.270 (0.000*)	−0.250 (0.008*)	0.197 (0.048*)	−0.221 (0.000*)
	Group variance	0.016	0.019	0.018	0.015								
Language	Objective index	0.073 (0.259)	0.059 (0.385)	0.073 (0.219)	0.039 (0.620)	0.131	0.133	0.007*	0.019*	0.106 (0.036*)	0.112 (0.024*)	0.172 (0.000*)	0.091 (0.180)
	Subjective index	−0.039 (0.587)	−0.002 (0.981)	−0.078 (0.255)	−0.093 (0.229)					−0.050 (0.387)	−0.058 (0.515)	−0.053 (0.382)	−0.127 (0.022*)
	Group variance	0.008	0.008	0.008	0.008								
Perceptual motor	Objective index	−0.190 (0.580)	0.025 (0.943)	−0.073 (0.808)	−0.158 (0.691)	0.027*	0.092	0.120	0.766	−0.867 (0.009*)	−0.677 (0.035*)	−0.637 (0.031*)	−0.323 (0.461)
	Subjective index	0.096 (0.796)	0.378 (0.346)	0.042 (0.904)	−0.277 (0.512)					−0.035 (0.910)	0.506 (0.258)	−0.176 (0.668)	0.019 (0.956)
	Group variance	0.356	0.369	0.363	0.381								
Social cognition	Objective index	−0.078 (0.116)	−0.065 (0.231)	−0.047 (0.324)	−0.065 (0.330)	0.065	0.512	0.507	0.270	−0.072 (0.190)	−0.055 (0.353)	−0.044 (0.386)	−0.065 (0.300)
	Subjective index	−0.095 (0.071)	0.000 (0.995)	0.037 (0.553)	−0.071 (0.154)					−0.094 (0.051)	−0.006 (0.923)	0.038 (0.516)	−0.071 (0.156)
	Group variance	0.000	0.001	0.000	0.000								
Creativity	Objective index	0.092 (0.055)	0.045 (0.257)	0.020 (0.636)	0.007 (0.904)	0.000*	0.001*	0.096	0.038*	0.230 (0.000*)	0.157 (0.000*)	0.106 (0.028*)	0.024 (0.757)
	Subjective index	−0.103 (0.047*)	−0.007 (0.883)	−0.046 (0.348)	−0.118 (0.050*)					−0.090 (0.084)	0.014 (0.810)	−0.009 (0.900)	−0.118 (0.014*)
	Group variance	0.010	0.007	0.011	0.010								
Reasoning	Objective index	0.004 (0.932)	0.000 (0.994)	−0.009 (0.831)	−0.003 (0.950)	0.991	0.072	0.259	0.178	−0.006 (0.923)	0.100 (0.118)	−0.007 (0.917)	−0.120 (0.113)
	Subjective index	−0.042 (0.415)	0.021 (0.704)	−0.072 (0.125)	0.054 (0.359)					0.002 (0.975)	0.123 (0.174)	−0.129 (0.139)	−0.091 (0.144)
	Group variance	0.017	0.016	0.020	0.021								
Comprehension	Objective index	0.148 (0.085)	0.129 (0.156)	0.057 (0.465)	0.006 (0.953)	0.002*	0.037*	0.267	0.103	0.223 (0.004*)	0.208 (0.007*)	0.118 (0.111)	0.036 (0.754)
	Subjective index	−0.171 (0.060)	−0.015 (0.886)	−0.034 (0.715)	−0.161 (0.103)					−0.137 (0.078)	0.005 (0.952)	−0.004 (0.972)	−0.145 (0.050*)
	Group variance	0.008	0.009	0.010	0.010								

Note: MWL for mental workload; DR for drowsiness; MFS for mental fatigue stress; VF for visual fatigue; * for statistically significant *p*-value.

significant impact on psychophysiological responses. This might have happened because the lighting environment created in the experiment of this study did not provide enough stimulation to induce changes in psychophysiological response.

These relationships are consistent with most of the findings from previous studies, but there are also a number of studies that have contradictory results [19,21,23,67]. These differences in trends might have shown due to different range of lighting conditions. For example, Fu et al. (2023) investigated differences in attention under different lighting conditions and their designed CCT range was from 3,300K to 5,300K which are lower than that of this study [67]. In that specific range, linear correlation between attention and CCT was revealed, but this correlation can differ by the range of CCT.

4.1.2. Research question 2: How do psychophysiological responses and cognitive performance affect each other?

This study explored the mutual influence between psychophysiological responses and cognitive performance. For example, if occupants feel DR or experience VF, cognitive performance may change, and at the same time, MWL and MFS may occur in the process of increasing cognitive performance to a certain level. The analysis of the mutual relationship with MLM and MRA found that overall, psychophysiological responses and cognitive performance have a bi-direction effect, not a unilateral effect. There was a higher degree of statistical significance in

Table 4
Impact of cognitive performance on psychophysiological response analyzed by mixed linear model.

Psychophysiological response		Parameter	Independent variables								
			AT	EX	ME	LAN	PM	SOC	CR	RE	COM
MWL	Objective index	Coefficient	0.075	0.049	−0.024	0.021	−0.003	−0.014	0.162	−0.002	−0.066
		p-value	0.018*	0.167	0.463	0.548	0.673	0.561	0.021*	0.971	0.187
		Group variance	0.001								
	Subjective index	Coefficient	0.043	−0.195	−0.180	−0.052	0.001	−0.119	−0.093	−0.142	−0.067
		p-value	0.626	0.056	0.035*	0.595	0.973	0.079	0.629	0.291	0.625
		Group variance	0.019								
DR	Objective index	Coefficient	0.047	0.069	−0.029	0.015	0.004	−0.008	0.111	0.053	−0.034
		p-value	0.188	0.079	0.437	0.711	0.585	0.788	0.156	0.340	0.550
		Group variance	0.001								
	Subjective index	Coefficient	−0.087	−0.224	−0.033	0.006	0.011	−0.004	0.055	0.082	−0.033
		p-value	0.283	0.036*	0.673	0.949	0.555	0.949	0.756	0.461	0.802
		Group variance	0.005								
MFS	Objective index	Coefficient	0.189	0.125	0.048	0.155	−0.013	−0.057	0.332	0.045	−0.152
		p-value	0.091	0.304	0.682	0.372	0.602	0.520	0.163	0.776	0.393
		Group variance	0.011								
	Subjective index	Coefficient	0.075	0.056	0.112	−0.113	−0.004	0.038	0.027	−0.167	−0.048
		p-value	0.421	0.567	0.199	0.278	0.845	0.608	0.888	0.180	0.746
		Group variance	0.004								
VF	Objective index	Coefficient	0.089	0.075	0.025	0.015	−0.003	−0.018	0.120	−0.015	−0.061
		p-value	0.038*	0.105	0.559	0.766	0.715	0.609	0.182	0.794	0.382
		Group variance	0.001								
	Subjective index	Coefficient	0.032	0.015	−0.059	−0.038	−0.002	−0.014	−0.094	0.011	0.022
		p-value	0.407	0.737	0.117	0.376	0.800	0.638	0.278	0.857	0.710
		Group variance	0.010								

Note: AT for attention; EX for executive ability; ME for memory; LAN for language; PM for perceptual motor; SOC for social cognition; CR for creativity; RE for reasoning; COM for comprehension; MWL for mental workload; DR for drowsiness; MFS for mental fatigue stress; VF for visual fatigue; * for statistically significant *p*-value.

Table 5
Impact of cognitive performance on psychophysiological response analyzed by multiple regression model.

Psychophysiological response		Parameter	Independent variables								
			AT	EX	ME	LAN	PM	SOC	CR	RE	COM
MWL	Objective index	*p*-value	0.000*								
		Coefficient (*p*-value)	0.061 (0.066)	0.078 (0.016*)	0.027 (0.327)	0.016 (0.627)	−0.010 (0.090)	−0.019 (0.478)	0.234 (0.000*)	0.043 (0.203)	−0.088 (0.177)
	Subjective index	*p*-value	0.000*								
		Coefficient (*p*-value)	0.041 (0.689)	−0.413 (0.000*)	−0.206 (0.012*)	−0.113 (0.316)	−0.029 (0.129)	−0.175 (0.040*)	−0.084 (0.678)	−0.122 (0.238)	−0.086 (0.632)
DR	Objective index	*p*-value	0.000*								
		Coefficient (*p*-value)	0.028 (0.439)	0.090 (0.018*)	0.018 (0.549)	0.032 (0.347)	0.000 (0.944)	−0.014 (0.664)	0.174 (0.042*)	0.128 (0.001*)	−0.059 (0.416)
	Subjective index	*p*-value	0.001*								
		Coefficient (*p*-value)	−0.097 (0.214)	−0.285 (0.000*)	−0.045 (0.463)	−0.032 (0.726)	0.001 (0.962)	−0.028 (0.664)	0.120 (0.435)	0.086 (0.280)	−0.063 (0.618)
MFS	Objective index	*p*-value	0.000*								
		Coefficient (*p*-value)	0.196 (0.050*)	0.156 (0.129)	0.189 (0.048*)	0.213 (0.032*)	−0.031 (0.127)	−0.070 (0.452)	0.386 (0.094)	0.130 (0.285)	−0.170 (0.382)
	Subjective index	*p*-value	0.556								
		Coefficient (*p*-value)	0.035 (0.650)	0.034 (0.665)	0.097 (0.232)	−0.092 (0.273)	−0.004 (0.836)	0.047 (0.539)	0.094 (0.607)	−0.124 (0.240)	−0.094 (0.572)
VF	Objective index	*p*-value	0.001*								
		Coefficient (*p*-value)	0.091 (0.032*)	0.096 (0.008*)	0.055 (0.165)	0.027 (0.474)	−0.002 (0.744)	−0.014 (0.696)	0.086 (0.259)	−0.007 (0.923)	−0.042 (0.532)
	Subjective index	*p*-value	0.000*								
		Coefficient (*p*-value)	−0.012 (0.829)	−0.161 (0.006*)	−0.109 (0.014*)	−0.152 (0.018*)	−0.013 (0.168)	−0.061 (0.211)	−0.285 (0.010*)	−0.196 (0.000*)	0.130 (0.192)

Note: AT for attention; EX for executive ability; ME for memory; LAN for language; PM for perceptual motor; SOC for social cognition; CR for creativity; RE for reasoning; COM for comprehension; MWL for mental workload; DR for drowsiness; MFS for mental fatigue stress; VF for visual fatigue; * for statistically significant *p*-value.

the impact of psychophysiological responses on cognitive performance as independent variables, and unlike lighting, psychophysiological responses were found to have a significant impact not only on primary cognitive performance but also on complex cognitive performance. This suggests that when occupants' work productivity is managed in an office where complex cognitive performance is important, it is necessary to measure and consider occupants' physiological responses and psychological responses beyond uniform lighting control. In addition, most of the objective integrated indices showed a positive correlation with cognitive performance, while subjective integrated indices showed a negative correlation. This suggests that cognitive performance decreases as MWL, DR, MFS and VF perceived by occupants increase. Moreover, there was a positive correlation in objective integrated indices. This is because a certain level of engagement is involved to perform cognitive performance. For example, visual work must be involved to achieve cognitive performance above a certain level. Notably, among the complex cognitive performances. Creativity showed statistical significance with all psychophysiological responses. While creativity showed statistical significance in a positive correlation with the objective indices of MWL, DR, MFS, it showed statistical significance in a negative correlation with the subjective indices of MWL and VF. That is, if occupants feel excessive MWL and VF, creativity may decrease. The investigation of psychophysiological responses that can occur in a cognitive performance test found that in most cases, objective integrated indices showed a positive correlation, while subjective integrated indices showed a negative correlation. This is a phenomenon that occurs when the physiological response is naturally activated while a cognitive performance test is being carried out. Conversely, when occupants demonstrate better cognitive performance, they perceive less MWL, DR and VF. Notably, among physiological responses, the subjective integrated indices of VF showed the highest degree of cognitive performance and statistical significance. Because psychophysiological response and cognitive performance have a very complex multi-layer structure, it is impossible to accurately distinguish between independent and dependent variables. However, these research results suggest that consideration of psychophysiological responses is essential for managing cognitive performance.

This research suggested that psychophysiological responses and cognitive performances have mutual relationships which means independent variables and dependent variables cannot be identified on absolute basis. Liu et al. (2021) investigated the oscular performance and cognitive performance and found out there are three zones; (i) where oscular performance and work efficiency increase together, (ii) where oscular performance starts to reduce, but work efficiency maintains to increase and (iii) where they reduce together [16]. Cognitive performances require oscular performance which induces VF and when people keep working on task, MWL increases gradually. However, there is a point where these psychophysiological responses exceed the limit line and affects cognitive performances negatively [70]. This is why psychophysiological responses should be managed to enhance occupants' cognitive performances. These underlying mechanisms are quite complex as the psychophysiological responses themselves include many bio-signals and self-reported evaluations. They have to be defined by other indices which means they are almost impossible to be evaluated by itself [71]. Also, these mechanisms are highly related to stress, hormone responses and emotional regulations [72,73]. These implications derive the need for multidimensional analysis.

4.2. Directions for developing smart office lighting systems

As demand for smart buildings, cities and homes has increased, research has been actively conducted regarding indoor environment control that can maximize occupants' cognitive performance. Based on the results of this study, directions for future studies are suggested as follows. Firstly, lighting does not solely work on cognitive performance, but with psychophysiological responses. That is, controlling lighting environment in a specific manner does not provide consistent help in improving cognitive performance, but managing psychophysiological responses together can more effectively improve cognitive performance. Accordingly, it is necessary to measure physiological responses in real time, derive occupants' MWL, DR, MFS and VF and then manage cognitive performance. Secondly, in this process, data related to psychological responses are needed as well. Meanwhile, in the case of physiological responses, it is possible to ensure real-time data collection and even continuous data collection using appropriate equipment. On the other hand, the collection of psychological responses is inefficient as it involves occupants diagnosing their own conditions and responding by means of a certain method. Accordingly, it is necessary to develop a model for predicting subjective MWL, DR, MFS and VF using physiological responses. Finally, the investigation of the impact of lighting on cognitive performance using MLM found that there is variance depending on the individual. This is significant in limiting bias in the results due to differences in individual capabilities when investigating the impact of lighting on cognitive performance and at the same time suggests that the lighting environment may not have the same impact on all occupants. In other words, a lighting environment that is generally close to daylight can have a positive impact on primary cognitive performance. However, since the impact of lighting is not consistent for all occupants, it may be difficult to maximize cognitive performance with only general lighting. Recently, as research has been undertaken to satisfy occupants' personal thermal comfort zone in thermal environments, it has been necessary to actively introduce task lighting in lighting environments to devise a personal comfort system.

4.3. Limitations of the study and future directions

Despite the originality and contributions of the main findings, this study has a number of limitations. First of all, the sample size of the experiment was relatively small, and statistical power of this study can be limited by the sample size. Even though this study tried to overcome the limitations that come from the sample size by statistical techniques such as bootstrapping, data obtained from more subjects can enhance the reliability of the analysis. Secondly, as there were nine lighting scenarios for each subject to experience and many types of cognitive performances had to be measured, the time for lighting exposure and cognitive tasks was relatively short. Thus, this study can suggest the short-term impact, but has clear limitations to extend the analysis to the long-term exposure. Lastly, the subjects were all in their 20s and 30s while the working population in offices range from 20s to 60s and over. The limited sample, not only in size but also in variations, is not sufficient for generalization. In the future study, a bigger number of subjects should be recruited for sufficient sample size and the features such as the age and eye health of the subject should be more various for analysis that can be generalized. Also, the long-term impacts should be investigated to reveal the effect of real-life office lightings. Moreover, the assessment method of psychophysiological responses should be revised in the future study. Unlike physiological responses such as pupil diameter, psychophysiological responses like MWL, DR, MFS and VF are complex concepts that consist of various bio-signals and subjective evaluations. There is a big diversity of assessment methods to measure psychophysiological responses and for accuracy and objectivity, these methods should be revised and compared.

5. Conclusion

In this study, relationships between general office lighting, psychophysiological response, and cognitive performance were investigated and analyzed. To achieve this aim, experiments were conducted on human subjects under nine types of office lighting conditions, and the results were analyzed using statistical techniques such as mixed linear model and multiple regression analysis. Consequently, office lighting had a significant impact on primary cognitive performance but did not have a significant impact on complex cognitive performance and psychophysiological responses. Also, it was found that primary cognitive performance improves with increasing CCT and illuminance. Psychophysiological responses and cognitive performance were found to have a mutual influence, and the impact of psychophysiological responses showed a slightly higher degree of statistical significance. In particular, psychophysiological responses were found to have a significant impact on complex cognitive performances such as creativity. This study has its originality in that diverse cognitive performances were observed in an environment very similar to an actual office, and psychophysiological responses were defined via objective and subjective integrated indices. In addition, this study poses future directions to develop smart office lighting systems based on the analyzed results. In the future, there will be limitations in uniformly controlling and managing occupants' cognitive performance through office lighting. Accordingly, there is a need to develop a system capable of automatically measuring psychophysiological responses and managing cognitive performance in a variety of ways.

CRediT authorship contribution statement

Dahyun Jung: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jongbaek An:** Writing – original draft, Visualization, Validation, Resources, Methodology. **Taehoon Hong:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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