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Impact of Indoor Thermal—Humidity and Lighting Environments on Cognitive Performance and Work Efficiency of Knowledge Workers in Open-Plan Offices: An Empirical Study Based on a Multifactorial Cross-Experimental Design

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Abstract

Background and Research Gap: With the rapid development of the knowledge economy, open-plan office spaces have become a dominant design trend due to their ability to facilitate communication and improve spatial efficiency. However, the potential negative effects of complex indoor physical environments—particularly thermal—humidity and lighting conditions—on the cognitive performance of knowledge workers have become increasingly evident. Existing studies predominantly focus on the isolated effects of single environmental factors on specific physiological indicators, lacking systematic experimental investigations into the interaction mechanisms of thermo—visual multisensory environments from an interdisciplinary design perspective.

Methods: This study employed a multifactorial cross-experimental design to systematically examine the interactive effects of different temperature conditions (22°C, 26°C, 30°C) and correlated color temperature (CCT)/illuminance combinations (3000K/300 lx, 4000K/500 lx, 6000K/750 lx) on cognitive performance within a controlled simulated open-plan office environment.

Experimental Protocol: A total of 90 healthy knowledge workers were recruited. Neurophysiological responses were continuously monitored using electroencephalography (EEG). Data were collected through a multimodal approach integrating standardized cognitive tasks—including the N-back working memory test and the Stroop executive control test—with subjective questionnaires.

Key Findings: The results reveal a significant nonlinear interaction effect between thermal–humidity and lighting environments in modulating cognitive performance. Under warm conditions (30°C), high CCT and high illuminance (6000K/750 lx) cool-white lighting significantly mitigated thermal stress–induced cognitive load, improving working memory accuracy by 12.4%. Under neutral thermal conditions (26°C), moderate CCT and illuminance (4000K/500 lx) yielded optimal cognitive efficiency and enhanced activation in the EEG Alpha band.

Significance: This study elucidates the synergistic regulatory mechanisms of multiple indoor physical environmental factors on higher-order cognitive functions. It provides a robust theoretical foundation for the design of adaptive environmental control systems in future intelligent office spaces, highlighting the substantial potential of integrating design disciplines with human factors engineering to enhance workplace health and productivity.

Keywords: Open-plan office; Thermal–humidity environment; Lighting environment; Cognitive performance; Electroencephalography (EEG); Cross-design

1. Introduction

In the context of the contemporary knowledge economy, human capital has become a key determinant of organizational competitiveness. Knowledge workers primarily engage in complex cognitive tasks that rely heavily on working memory, executive control, and sustained attention, and their work efficiency directly affects organizational innovation capacity and economic performance [1]. To facilitate communication and collaboration while optimizing spatial costs, open-plan offices have become the dominant model in office building design worldwide over the past decades [2, 3]. However, while this spatial configuration reduces physical barriers, it also exposes employees to more complex indoor physical environments that are difficult to individually regulate [4].

The impact of Indoor Environmental Quality (IEQ) on human health and performance has attracted extensive attention from architecture, environmental psychology, and human factors engineering [5, 6]. Among these, thermal—humidity and lighting environments constitute two core dimensions of the physical workplace. They not only determine physiological comfort but also play a critical role in regulating central nervous system arousal levels and the allocation of cognitive resources [7]. Inappropriate thermal conditions may induce heat stress, increase mental workload, and impair executive function [8, 9], while the non-visual effects of lighting influence melatonin secretion, circadian rhythms, and alertness via intrinsically photosensitive retinal ganglion cells (ipRGCs) [10, 11].

Although substantial research has been conducted in this domain, mainstream approaches predominantly rely on subjective questionnaire surveys or controlled experiments focusing on single environmental factors. For instance, numerous studies have demonstrated that deviations from neutral thermal conditions reduce task processing speed [8], while high correlated color temperature lighting can temporarily enhance alertness [12, 13]. However, several critical limitations and research gaps remain. First, most studies treat thermal and lighting environments as independent systems, overlooking cross-modal integration effects in human perception when processing multisensory environmental stimuli [14]. Second, evaluation metrics are often limited to subjective self-reports or simple behavioral performance, lacking objective physiological measurements of dynamic cortical neural activity [15]. Third, existing research rarely adopts a design innovation perspective to explore how dynamic coupling of environmental factors can compensate for the adverse effects of a single unfavorable condition [16].

To address these gaps, this study aims to establish a multifactorial cross-experimental framework from an interdisciplinary design perspective to systematically evaluate the interaction effects of thermal—humidity and lighting environments on the cognitive performance of knowledge workers. Specifically, this study focuses on working memory and executive control under varying combinations of temperature and lighting conditions (correlated color temperature/illuminance), while simultaneously collecting electroencephalography (EEG) data to uncover the underlying neurophysiological mechanisms. Acoustic conditions and indoor air quality (CO_2 concentration) were controlled as baseline variables to eliminate confounding effects [17]. We hypothesize that regulation of the lighting environment can, to a certain extent, compensate for the decline in cognitive performance caused by thermally uncomfortable conditions, and that this compensatory effect has observable neurobiological correlates in EEG spectral characteristics.

2. Literature Review and Related Work

2.1. Rationale for Topic Selection and Introduction of an Interdisciplinary Approach

To address this limitation, the present study introduces electroencephalography (EEG) as a cross-disciplinary analytical tool. The rationale is that behavioral data (e.g., reaction time and accuracy) are often confounded by participants' subjective motivation and compensatory effort, making it difficult to sensitively detect subtle fluctuations in cognitive load induced by environmental changes. In contrast, EEG provides high temporal resolution of cortical electrophysiological activity, enabling the identification of underlying neural mechanisms related to attentional allocation and working memory processing [15, 20]. This integrative approach, combining physiological measurement with environmental design, not only demonstrates strong innovation but also offers a feasible pathway for validating more precise adaptive control models in intelligent office environments [21] (Figure 1).

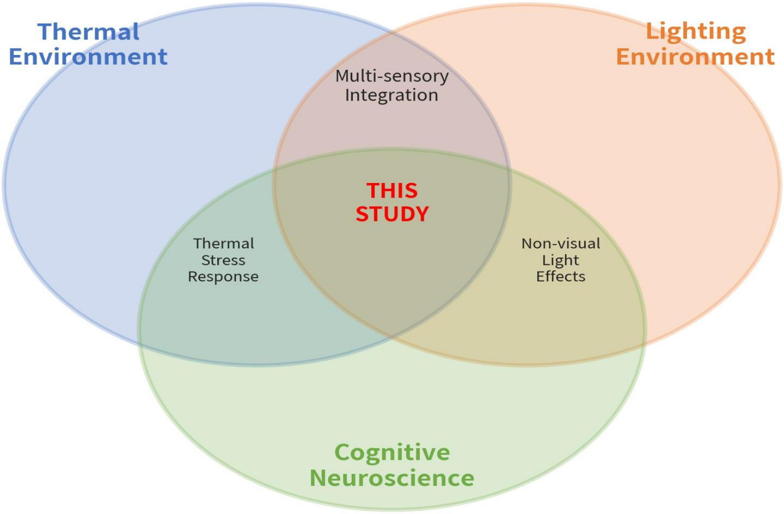

Figure 1. Venn Diagram of the Interdisciplinary Scope of This Study.

2.2. Related Work

2.2.1. Thermal Environment and Cognitive Performance

Indoor temperature is one of the most significant physical factors affecting work efficiency [22]. A meta-analysis by Porras-Salazar et al. indicates that deviations from the neutral temperature of 22°C significantly increase error rates and reduce work speed, particularly in tasks with high cognitive load [8]. Kawakubo et al. further demonstrated that in slightly warm environments around 26°C, although subjective comfort remains acceptable, executive control performance begins to exhibit subtle declines [9]. However, a recent review by Lin et al. suggests that moderate heat stress does not exert uniformly negative effects on cognitive performance; rather, its impact is highly dependent on task type and exposure duration [23].

From a neurophysiological perspective, Pourghorban et al. found that thermal discomfort significantly alters Alpha and Beta band power in frontal and parietal regions, indicating increased recruitment of cognitive resources to maintain task performance [15]. Although these studies have established a foundational understanding of the effects of thermal environments on cognition [24, 25], they largely neglect the potential moderating effects of other environmental factors [26].

2.2.2. Lighting Environment and Cognitive Performance

Lighting serves not only visual functions but also exerts non-visual effects on human physiological rhythms and alertness, which have become a major focus in recent lighting design research [27]. Bao et al. found that, compared to low correlated color temperature (3000K), high correlated color temperature (6000K) cool-white lighting effectively reduces mental workload and enhances sustained attention in office environments [12]. Experimental findings by Awada et al. further indicate that lighting strategies combining high illuminance and high CCT significantly promote cognitive recovery and reduce psychological stress [13].

In addition, a series of studies by Boubekri et al. highlight the irreplaceable role of daylight and outdoor views in maintaining high levels of cognitive function and sleep quality throughout the day [10, 11]. However, Zeng et al. pointed out that excessively high illuminance levels (>1000 lx) may induce visual fatigue and glare, thereby impairing cognitive performance [28]. This suggests that lighting design must strike a balance between visual comfort and non-visual arousal effects [29].

2.2.3. Multifactor Interaction and Open-Plan Offices

In open-plan office environments, the interaction of multiple environmental factors has begun to receive increasing attention [2]. A field study by Kang et al. on university open-plan research offices found that five dimensions of Indoor Environmental Quality (IEQ)—thermal, visual, acoustic, air quality, and spatial layout—collectively determine overall work efficiency [3]. Wang et al., in a systematic review, explicitly called for a paradigm shift in IEQ research from single-factor approaches to multifactor coupling frameworks [5].

Among the limited interaction studies available, Mohebian et al. investigated the combined effects of high temperature and lighting, revealing that higher lighting levels can partially offset the prolongation of reaction time caused by heat exposure [14]. Similarly, recent research by Zhao et al. demonstrated the combined influence of temperature and volatile organic compounds (VOCs) on cognitive performance [30]. Nevertheless, the neurophysiological mechanisms underlying the interaction between thermal—humidity and lighting environments in complex cognitive tasks (e.g., working memory) remain largely unexplored [19].

3. Methodology

3.1. Research Strategy

This study follows an overall research framework of "controlled modeling followed by multidimensional validation." A highly controlled simulated open-plan office environment (environmental chamber) was employed, adopting a multifactorial cross-over experimental design that integrates both within-subject and between-subject approaches. By systematically manipulating indoor temperature and lighting parameters, and eliciting specific brain activity states through standardized cognitive tasks, the study examines the interactive effects of thermal—humidity and lighting environments on the cognitive performance of knowledge workers across three dimensions: subjective perception, behavioral performance, and neurophysiology (Figure 2).This study has adhered to the ethical principles outlined in the Declaration of Helsinki. All participants provided informed consent prior to the experiment, and the research protocol was reviewed and approved by the institutional ethics review committee.

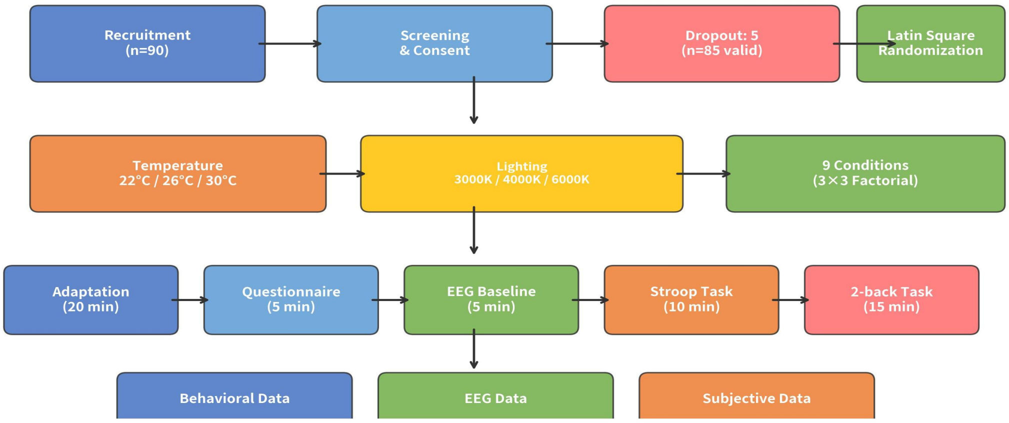

Figure 2. Experimental Procedure Flowchart.

3.2. Experimental Design and Data Collection Methods

1. Experimental Environment and Equipment

The experiment was conducted in an environmental chamber with dimensions of 6.0 m × 5.0 m × 2.8 m, which was furnished and arranged to simulate a typical open-plan office workspace. The chamber was equipped with a high-precision temperature and humidity control system (temperature control accuracy of ±0.5°C) and a spectrally tunable LED intelligent lighting system (correlated color temperature range: 2700K—6500K; illuminance range: 0—1500 lx). Background noise was strictly maintained below 40 dB(A), and carbon dioxide (CO_2) concentration was controlled below 800 ppm to eliminate the influence of acoustic conditions and indoor air quality.

2. Independent Variables (Experimental Conditions),A 3 × 3 full factorial design was employed in this study

- Thermal Environment (Temperature): Three levels were defined—cool (22°C), neutral (26°C), and warm (30°C). Relative humidity was maintained at a constant level of 50% ± 5%;
- Lighting Environment (CCT/Illuminance): Based on existing office lighting standards and research on non-visual effects, three representative combinations were selected—warm light with low illuminance (3000K, 300 lx; L1), neutral light with medium illuminance (4000K, 500 lx; L2), and cool light with high illuminance (6000K, 750 lx; L3). Desk illuminance uniformity was maintained above 0.7 in all conditions.

A total of nine environmental conditions were tested. To minimize order effects, the presentation sequence of conditions was fully randomized and counterbalanced using a Latin Square Design.

3. Participants (Biological Replicates)

An a priori power analysis was conducted using G*Power software (effect size $f = 0.25$, $\alpha = 0.05$, statistical power $1-\beta = 0.85$), indicating a minimum required sample size of 73 participants. To ensure sufficient statistical power and account for potential attrition, a total of 90 healthy knowledge workers were recruited (45 males and 45 females; age range: 24—38 years, mean age: 29.4 ± 3.6 years). All participants were right-handed, with normal or corrected-to-normal vision, no color vision deficiencies, and no history of neurological or psychiatric disorders. Participants were instructed to abstain from alcohol, caffeine, and vigorous physical activity for 24 hours prior to the experiment

4. Dependent Variables and Measurement Instruments

(1) The types of data collected in this study are specified as follows:

Behavioral Data (Core Indicators of Cognitive Performance):

- Working Memory: Assessed using the Spatial 2-back Task, with reaction time (RT) and accuracy (ACC) recorded;
- Executive Control: Evaluated באמצעות the classic Stroop color—word interference task, with the reaction time difference between congruent and incongruent conditions (Stroop Effect) measured.

(2) Physiological Data (Neural Mechanism Indicators):

Continuous electroencephalography (EEG) signals were recorded during cognitive tasks using a 64-channel EEG system (Neuroscan), with a sampling rate of 1000 Hz. The primary extracted metrics were the relative power spectral density (PSD) of Theta (4—8 Hz), Alpha (8—13 Hz), and Beta (13—30 Hz) bands in the frontal and parietal regions.

(3) Subjective Perception Data (Supplementary/Validation Measures):

Subjective environmental acceptability was assessed using the ASHRAE 7-point Thermal Sensation Vote (TSV) scale and a Visual Comfort Scale (VCS) questionnaire**.**

5. Experimental Procedure

All experiments were conducted between 9:00 AM and 11:30 AM to control for circadian rhythm effects. Each environmental condition lasted approximately 60 minutes and followed a standardized procedure: environmental adaptation period (20 min) → subjective questionnaire (5 min) → EEG baseline recording (5 min) → Stroop task (10 min) → 2-back task (15 min) → post-experiment questionnaire (5 min). A minimum washout period of 48 hours was maintained between any two consecutive experimental conditions.

3.3. Data Analysis Methods

The data processing procedures are as follows：

1. Data Preprocessing

For behavioral data, reaction times (RT) less than 200 ms or exceeding three standard deviations from the mean were excluded as outliers. EEG data were processed offline using EEGLAB: signals were downsampled to 250 Hz, band-pass filtered between 0.1—30 Hz, and artifacts from eye movements and muscle activity were removed באמצעות independent component analysis (ICA). Mean power values for specific frequency bands were then extracted.

2. Statistical Inference Models

- For behavioral and EEG indicators that satisfied assumptions of normality and homogeneity of variance, a two-way repeated measures ANOVA was conducted to examine the main effects of temperature, the main effects of lighting, and their interaction effects;
- When significant interaction effects were observed, simple main effects analyses were performed, with Bonferroni correction applied for multiple comparisons.
- Multiple linear regression analysis was employed to establish predictive models linking physical environmental parameters (T, CCT, E) with core cognitive performance indicators (e.g., 2-back accuracy). The coefficient of determination (R^2) was calculated to evaluate model fit.

3. Significance Threshold

All statistical analyses were conducted using SPSS 26.0, with the significance level set at $p < 0.05$.

4. Data

4.1. Descriptive Statistics

The data in this study were obtained from controlled experiments conducted in a simulated open-plan office environmental chamber between September and November 2025, with a total data collection period of eight weeks. The initial sample consisted of 90 participants. During the experiment, three participants were excluded due to substantial data loss caused by poor EEG electrode contact, and two participants withdrew due to personal reasons before completing all nine experimental conditions. Consequently, the final sample included in the analysis comprised 85 participants (n = 85; 42 males and 43 females).

Descriptive statistics for key variables are as follows:

- 2-back Task Accuracy (ACC, %): Mean = 82.4%, standard deviation (SD) = 12.6%, median = 84.1%, range = 58.3%—98.7%;
- 2-back Task Reaction Time (RT, ms): Mean = 685.4 ms, SD = 145.2 ms, median = 672.8 ms, range = 412.5—1105.3 ms;
- Stroop Effect (ms): Mean = 112.6 ms, SD = 38.5 ms;
- Frontal Theta Relative Power (%): Mean = 18.5%, SD = 4.2%;
- Parietal Alpha Relative Power (%): Mean = 24.3%, SD = 5.8%.

4.2. Data Preprocessing Methods

The raw data were cleaned and transformed as follows:

- For behavioral data, the distribution of reaction times for each participant under each experimental condition was first examined. Responses with reaction times less than 200 ms (considered anticipatory and invalid) and those exceeding the participant-specific mean ± 3 standard deviations were excluded as extreme outliers (accounting for approximately 2.1% of total trials);
- For EEG physiological data, preprocessing was conducted using the EEGLAB toolbox. The procedures included: downsampling to 250 Hz to reduce computational load; applying a 0.1—30 Hz band-pass filter to remove high-frequency noise and baseline drift; performing independent component analysis (ICA) to identify and remove artifact components related to eye blinks, eye movements, and muscle activity (with an average of 2—3 components removed per participant); and finally, transforming the time-domain signals into frequency-domain power spectral density באמצעות fast Fourier transform (FFT).

5. Results

5.1. Behavioral Cognitive Performance

Working Memory (2-back Task): Results from the two-way repeated measures ANOVA (Figures 3 and 4) revealed a significant main effect of temperature (F(2, 168) = 15.42, $p < 0.001$, $\eta^2 = 0.155$) and a significant main effect of lighting (F(2, 168) = 8.76, $p < 0.001$, $\eta^2 = 0.094$). More importantly, a significant interaction effect between temperature and lighting was observed (F(4, 336) = 6.28, $p < 0.001$, $\eta^2 = 0.070$).

Simple main effects analysis revealed the following patterns and trends:

- Under warm conditions (30°C), low correlated color temperature and low illuminance (L1: 3000K/300 lx) resulted in the lowest accuracy (72.9% ± 13.8%). However, when switching to high CCT and high illuminance (L3: 6000K/750 lx), accuracy significantly increased to 84.4% ± 10.4% ($p < 0.001$), representing an improvement of approximately 11.5% and demonstrating a strong compensatory effect;
- Under neutral conditions (26°C), moderate lighting (L2: 4000K/500 lx) yielded the optimal accuracy (88.1% ± 9.2%). Further increases in CCT and illuminance (L3) did not produce additional benefits;
- Under cool conditions (22°C), changes in lighting conditions did not significantly affect accuracy ($p > 0.05$); however, high CCT (L3) significantly reduced reaction time.

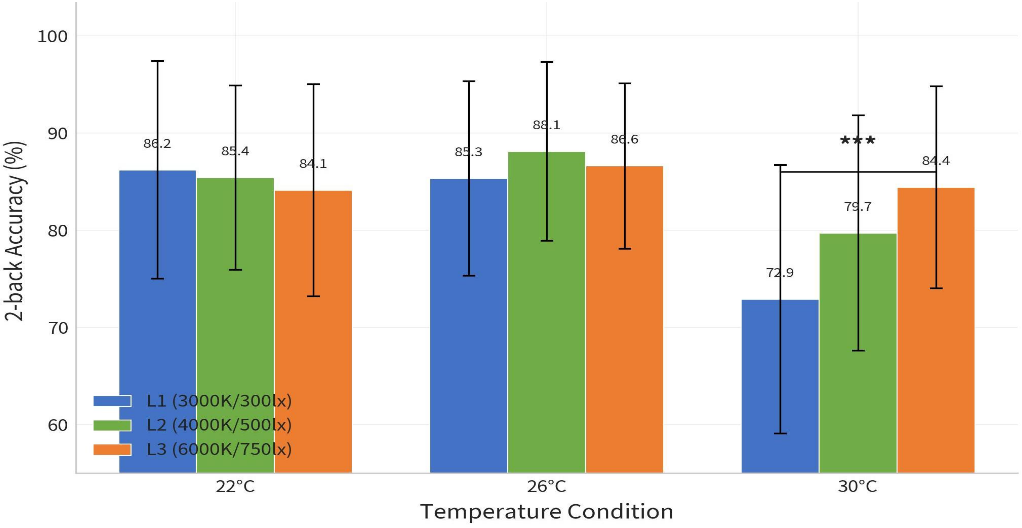

Figure 3. Comparison of 2-back Task Accuracy under Different Temperature and Lighting Conditions.

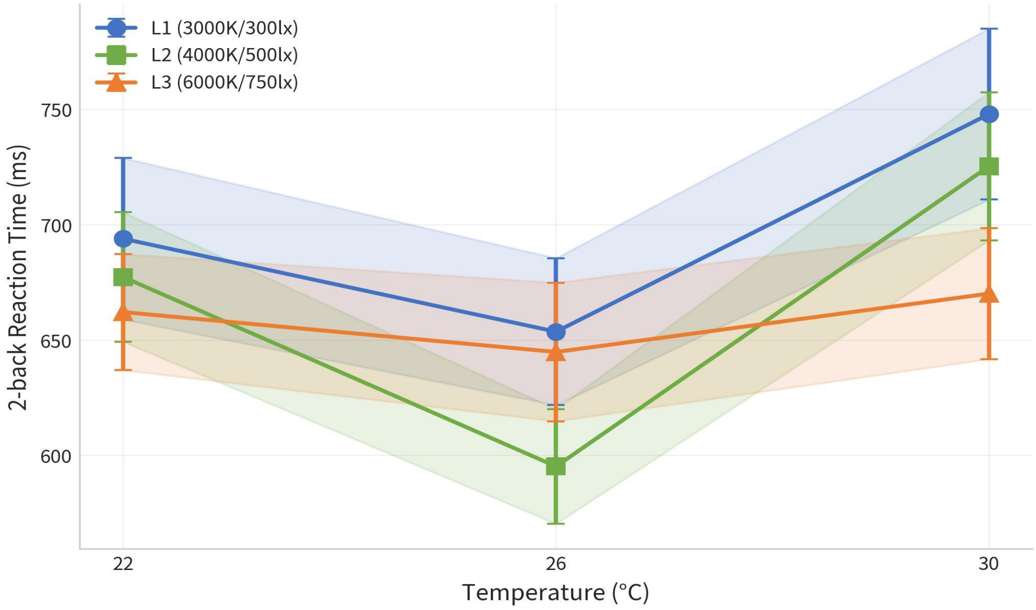

Figure 4. Reaction Time Trends of the 2-back Task under Different Temperature and Lighting Conditions.

Executive Control (Stroop Task): For the Stroop effect (where larger values indicate weaker interference control), a significant interaction effect between temperature and lighting was also observed (F(4, 336) = 4.95, *p* = 0.001). Under high-temperature conditions (30°C), the Stroop effect was greatest under L1 lighting (134.1 ± 42.4 ms), indicating substantial impairment in executive control. In contrast, L3 lighting significantly reduced the Stroop effect to 104.4 ± 36.2 ms (*p* < 0.001), demonstrating a clear mitigating effect (Figure 5).

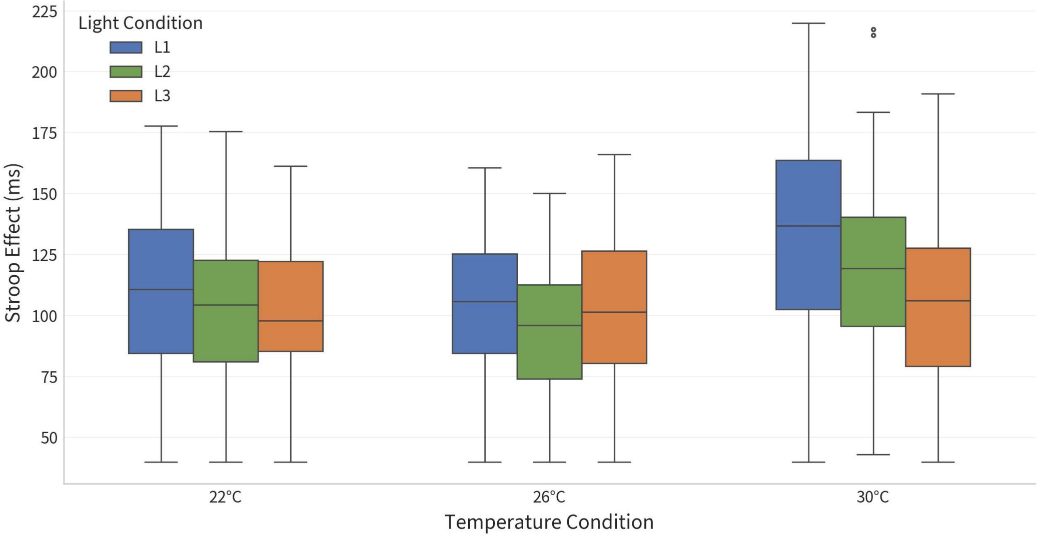

Figure 5. Boxplot Distribution of Stroop Effect Values.

5.2. EEG Physiological Results

Frequency-domain analysis of EEG data objectively corroborated the behavioral findings and further revealed underlying neural activity patterns:

- Frontal Theta Band (indicator of cognitive load and fatigue):Under 30°C with L1 lighting, the relative power of frontal Theta reached its peak (22.79% ± 4.00%), indicating that the combination of heat stress and dim lighting induced a high level of cognitive load. When L3 cool–white lighting was introduced, Theta power significantly decreased to 18.89% ± 3.69% ($p < 0.001$), suggesting that a high–arousal lighting environment effectively alleviated mental fatigue (Figure 6);
- Parietal Alpha Band (indicator of relaxation and attentional readiness):Under neutral temperature conditions (26°C) combined with L2 lighting, parietal Alpha activity was most pronounced (28.11% ± 6.15%). This finding is highly consistent with the optimal behavioral accuracy observed under this condition, reflecting a brain state characterized by moderate arousal and efficient resource allocation, indicative of a "flow–like" preparatory state (Figure 7).

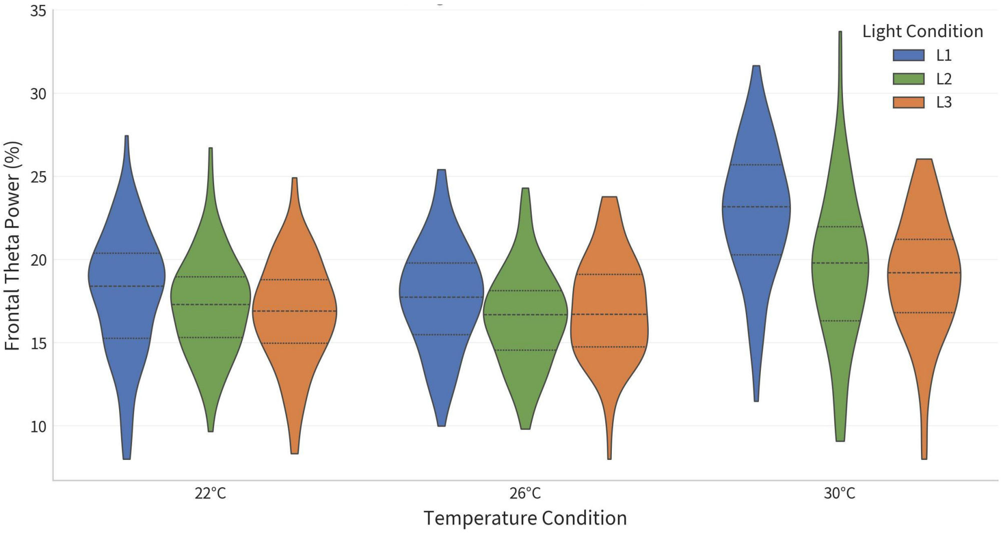

Figure 6. Violin Plot of Frontal Theta Power Distribution.

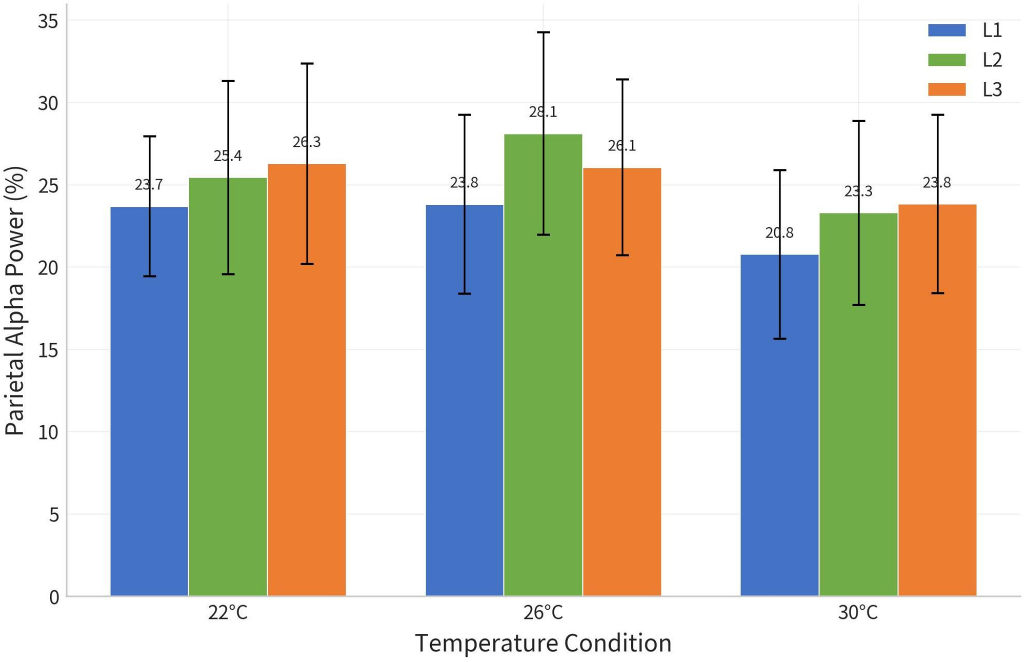

Figure 7. Bar Chart of Parietal Alpha Power.

5.3. Correlation Analysis and Predictive Modeling

The correlation heatmap (Figure 8) provides a visual representation of the relationships among variables. The 2-back task accuracy showed a significant negative correlation with frontal Theta power (r = —0.17) and a positive correlation with illuminance and correlated color temperature (r = 0.12).

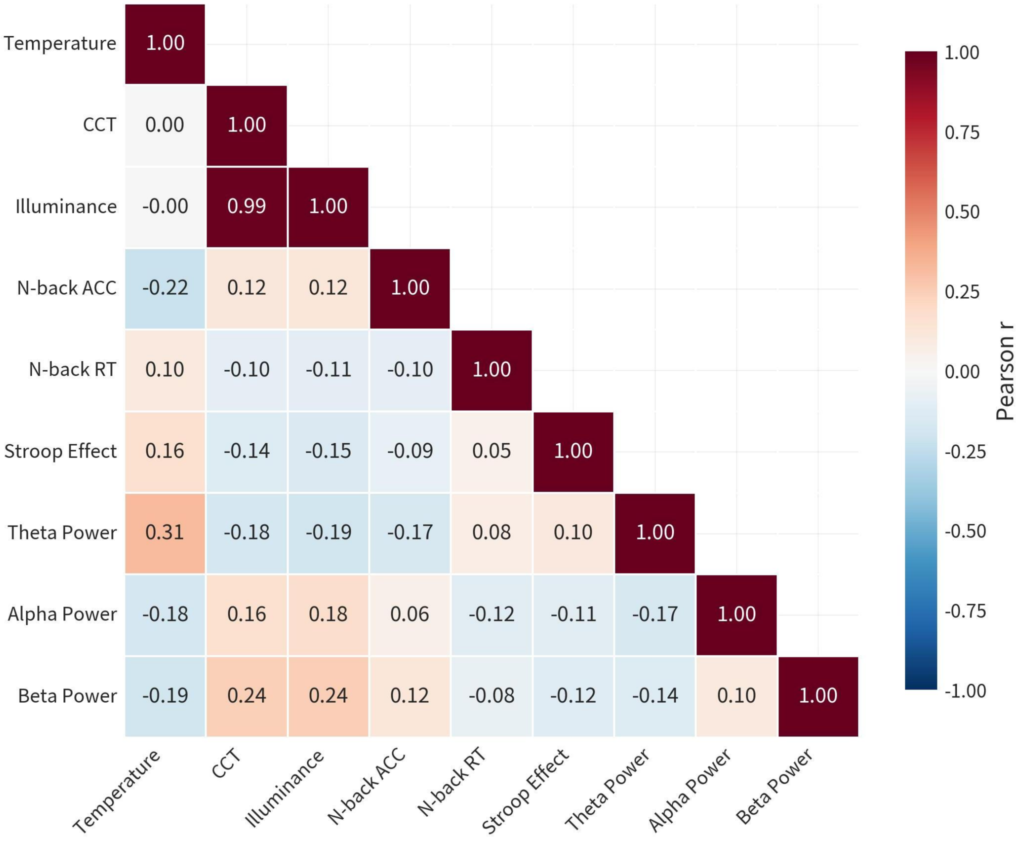

Figure 8. Correlation Heatmap of Key Variables.

To quantify the overall predictive capacity of environmental parameters on work efficiency, a multiple regression model was established with 2-back accuracy as the dependent variable. Physical environmental parameters—including temperature deviation ($\Delta T = |T - 26|$), correlated color temperature (CCT), and illuminance (E)—along with their interaction terms, were entered as independent variables.

The model demonstrated a good fit (adjusted $R^2 = 0.412$, $F = 24.5$, $p < 0.001$). The regression results indicated that temperature deviation was the strongest negative predictor, while the interaction term between CCT and temperature deviation (CCT × ΔT) showed a significant positive predictive effect. This finding further statistically confirms the compensatory regulatory mechanism of cool-white lighting under thermally uncomfortable conditions. The contour plot (Figure 9) clearly illustrates this interaction effect surface.

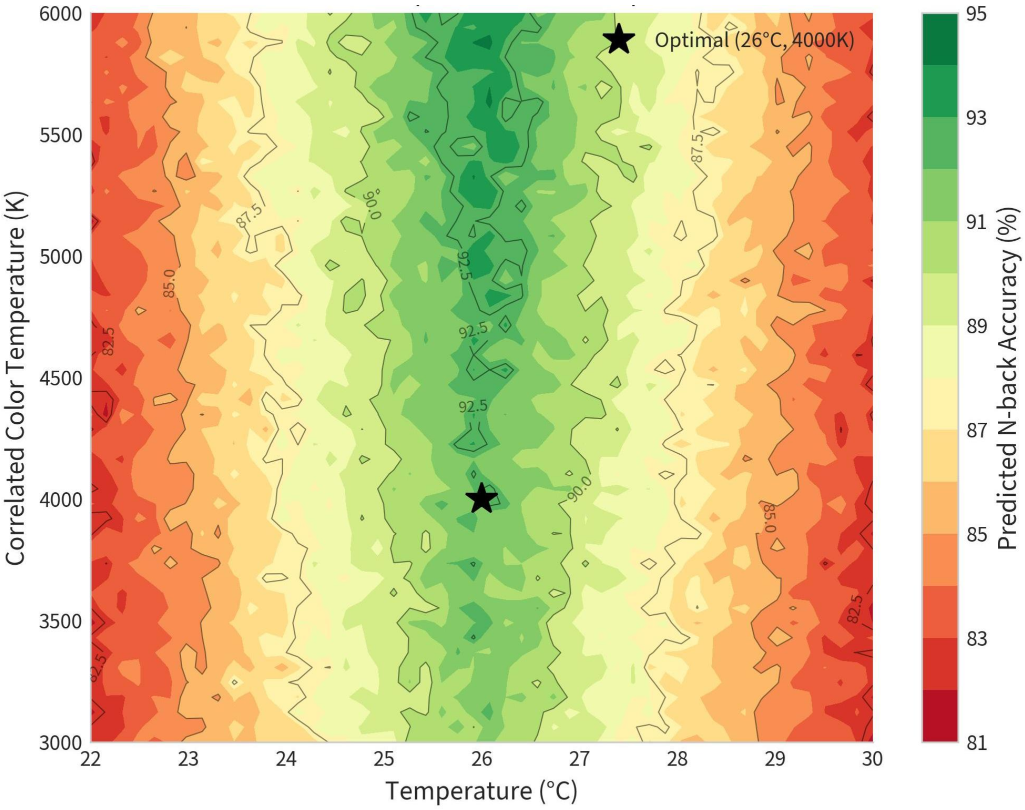

Figure 9. Contour Plot of Cognitive Performance Prediction Based on the Regression Model.

6. Discussion

6.1. Interpretation of Results and Cross-Study Comparison

The core finding of this study is the presence of a significant nonlinear interaction effect between thermal—humidity and lighting environments on the cognitive performance of knowledge workers. In particular, high correlated color temperature and high illuminance lighting demonstrate a compensatory effect on cognitive decline induced by heat stress.

In comparison with existing literature, the main effect of temperature observed in this study is consistent with the meta-analysis by Porras-Salazar et al. (2021), which concluded that deviations from neutral temperature (e.g., 30°C) significantly impair cognitive task accuracy [8]. Regarding the main effect of lighting, the present findings support Bao et al. (2021), who reported that high correlated color temperature lighting can reduce mental workload [12]. However, unlike prior studies that examined these factors in isolation, this study is the first to reveal—through a cross-over experimental design—the heterogeneity of lighting-induced arousal effects under different thermal conditions.

Awada et al. (2025) previously suggested that cool-white lighting enhances cognitive performance [13]. The present study further refines this conclusion by identifying its boundary conditions: under neutral thermal conditions (26°C), excessively high CCT and illuminance (6000K/750 lx) do not improve working memory performance and may instead induce visual fatigue, leading to slower responses. Rather, the primary benefit of such lighting lies in counteracting drowsiness and reduced executive function under warm conditions (30°C) (Figure 10).

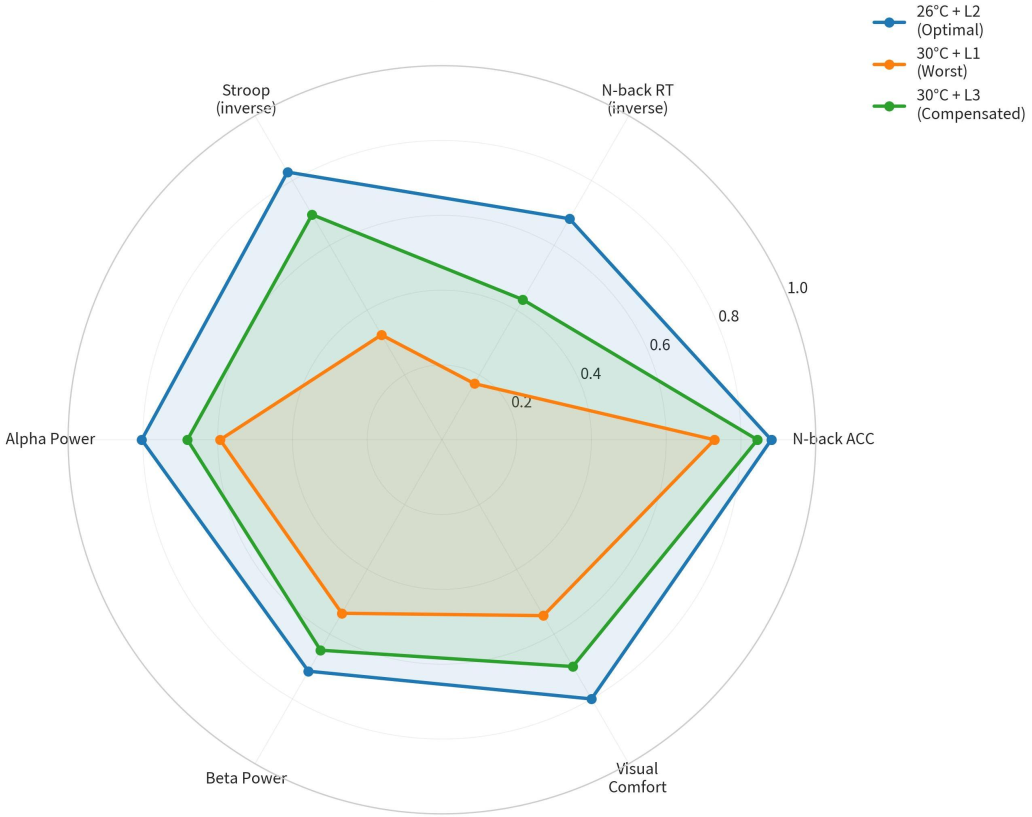

Figure 10. Radar Chart Comparison of Multidimensional Performance under Key Conditions.

6.2. Longitudinal Associations and Neural Mechanisms

A high degree of longitudinal consistency was observed between behavioral outcomes and EEG physiological indicators in this study. Under the combined condition of 30°C and 3000K warm lighting, the increase in Stroop effect and the decrease in 2-back accuracy corresponded closely with a marked elevation in frontal Theta power. Increased Theta activity is commonly regarded as a biological marker of cortical inhibition and cognitive resource depletion.

When the lighting condition was adjusted to 6000K/750 lx, the blue-enriched spectrum stimulated intrinsically photosensitive retinal ganglion cells (ipRGCs), activating the suprachiasmatic nucleus (SCN) and the locus coeruleus, and subsequently engaging the ascending reticular activating system (ARAS). This light-driven neural arousal mechanism effectively suppressed excessive Theta activity at the physiological level. As a result, it counteracted the parasympathetic dominance induced by heat stress, enabling the brain to re-engage executive control networks and sustain high levels of working memory performance.

6.3. Attribution of Differences and Design Implications

When comparing the present findings with studies reporting negligible effects of thermal environments on cognition (e.g., subgroup analyses by Lin et al.), the discrepancy may primarily stem from differences in task complexity and the involvement of multisensory compensatory mechanisms. Simple reaction tasks may be less sensitive to heat stress, whereas the 2-back task employed in this study requires continuous updating of working memory and is therefore more susceptible to environmental stressors.

From the perspective of interdisciplinary design innovation, these findings hold significant practical implications. Conventional open-plan office environments typically adopt static, uniform environmental control strategies (e.g., maintaining constant conditions such as 24°C and 500 lx). The present study suggests that future intelligent office design should shift toward a “multisensory dynamic coupling” strategy. For example, during peak electricity demand in summer, building systems could allow indoor temperatures to rise moderately (e.g., 28—30°C) to achieve energy savings, while simultaneously increasing lighting CCT and illuminance through intelligent lighting systems. This approach enables a balance between building sustainability and human-centered performance, maintaining cognitive efficiency without compromising energy efficiency or occupant well-being.

7. Conclusion

7.1. Key Findings

Through a rigorous multifactorial cross-experimental design combined with EEG physiological measurements, this study confirms that indoor thermal—humidity and lighting environments exert a significant joint regulatory effect on the cognitive performance of knowledge workers in open-plan offices. The findings indicate that under warm conditions (30°C), high correlated color temperature and high illuminance lighting (6000K/750 lx) can serve as an effective environmental intervention, significantly alleviating heat-induced cognitive load, improving working memory accuracy, and reducing frontal Theta power. In contrast, under neutral thermal conditions (26°C), moderate lighting parameters (4000K/500 lx) are sufficient to maintain optimal Alpha-band activation and executive performance.

7.2. Implications

At the theoretical level, this study extends Environmental Stress Theory by validating the neural mechanisms of cross-modal multisensory integration in regulating higher-order cognitive functions. From a practical perspective, the findings provide empirical support for adaptive environmental control systems in intelligent office spaces. Specifically, the concept of "compensating thermal stress with lighting" through dynamic multi-physical field coupling offers a novel strategy to simultaneously ensure employee well-being and productivity while enabling more flexible energy-saving building operations, highlighting the significant value of interdisciplinary integration between design and engineering.

7.3. Limitations

This study has several limitations. First, in terms of scope, the sample consisted primarily of young knowledge workers aged 24—38 years and did not include middle-aged or older populations. Additionally, the simulated open-plan office environment excluded acoustic disturbances, which limits ecological validity compared to real-world settings characterized by background noise. Second, regarding methodology and data, the study focused only on short-term exposure effects (within 1 hour) and did not assess long-term outcomes, such as chronic physiological adaptation or cumulative visual fatigue under prolonged exposure to dynamically coupled environments.

7.4. Future Research

Based on these limitations, future research should focus on:

- conducting longitudinal field studies in real open-plan office environments to evaluate the long-term effects of dynamic light—thermal coupling strategies on employee productivity and mental health;

- incorporating acoustic factors (e.g., white noise and speech interference) as a third dimension to develop more comprehensive thermo—visual—acoustic interaction models for cognitive performance prediction;
- integrating wearable devices and machine learning algorithms to develop personalized, adaptive environmental control systems based on real-time physiological feedback (e.g., heart rate variability and micro-expressions).

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