Interaction Effects of Indoor Environmental Quality Factors on Cognitive Performance and Perceived Comfort of Young Adults in Open Plan Offices in North American Mediterranean Climate

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ABSTRACT

While Indoor Environmental Quality (IEQ) factors in an environment co-exist, the interaction effects of these factors and their impacts on cognitive functioning and perceived comfort have not been comprehensively examined. In this study, the interaction effects between temperature, lighting Correlated Color Temperature (CCT), and noise levels on selective attention, sustained attention, creativity, acoustics, thermal, visual, and overall IEQ comfort of young adults in open-plan offices in North American Mediterranean climate were presented. In a mixed-design controlled experimental setting, 52 young adults were recruited, and their objective cognitive performance and subjective comfort were assessed through statistical analysis. The experimental set points included [20 °C, 25 °C], [2700 K, 6500 K], and [50 dB, 65 dB] for temperature, lighting color, and noise, respectively. Additionally, the work took into consideration the gender and Body Mass Index (BMI) of participants. The results show that temperature moderated the effect of noise level and lighting CCT on selective attention, while no effect of IEQ factors on sustained attention was found. Creativity was influenced by gender and its interaction with the noise level. Concerning perceived comfort, acoustic comfort varied significantly with temperature. Thermal comfort was influenced by the combined moderating effect of lighting CCT and BMI on temperature, while visual comfort was driven by the moderation effect of gender on lighting CCT. Overall comfort was affected by the noise level and temperature. Finally, cognitive performance indicators were correlated with perceived IEQ comfort votes. Based on the findings of this study, considerations of interactions between noise, lighting CCT, temperature, gender, and BMI can shape occupant-centric priorities for enhanced cognitive functioning and comfort.

Graphical Abstract:

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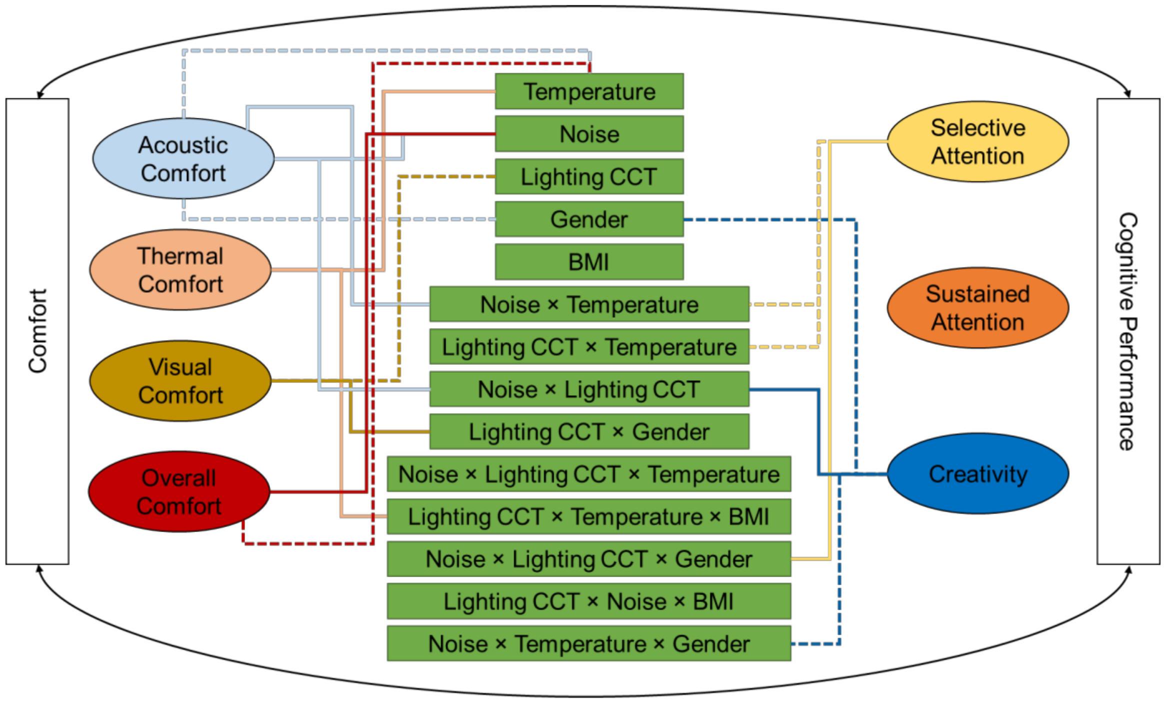


Keywords: Indoor Environmental Quality; Indoor Environment; Cognitive Functions; Performance; Comfort; Interaction Effect.

INTRODUCTION

The influence of Indoor Environmental Quality (IEQ) factors on the learning experience in educational settings has been well-documented [1]. Looking ahead to 2030, the implementation of improved IEQ factors in workspaces holds great potential to not only enhance performance but also generate significant benefits totaling $90 billion [2]. Consequently, researchers have extensively explored the individual impacts of specific IEQ factors on various indicators of cognitive performance and perceived comfort [3], [4]. However, it is crucial to recognize that the human sensory system is exposed to multiple indoor environmental factors, and therefore, occupants' cognitive functioning and perceived comfort are influenced by the combined effects of these factors rather than a simple sum of their individual contributions. This necessitates a comprehensive evaluation of the interactions between different domains of IEQ [5]. For instance, the interplay between noise and temperature can have an impact on cognitive performance, specifically attention levels [6]. In light of these considerations, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Guideline underscores the importance of understanding the interaction effects among IEQ factors on human comfort, well-being, and productivity. Consequently, it recommends conducting more detailed research in this area [7].

Cognitive functions refer to multiple mental abilities and cognitive domains, including learning, thinking, reasoning, remembering, problem-solving, decision-making, attention, executive functions, and creativity [8]–[10]. Attention and creativity are two of the main cognitive functions and abilities that drive performance and productivity in office and educational settings [11], [12]. Attention involves multiple domains, including selective attention and sustained attention. *Selective attention* is defined as concentration on certain stimuli in the environment and not on others, enabling important stimuli to be distinguished from peripheral or incidental ones [13]. Among the factors reported to hinder attention, increased temperature, presence of noise, and lower lighting Correlated Color Temperature (CCT) stand out prominently [14]–[16]. *Sustained attention* is defined as an attentional focus on a task for an extended length of time [13]. Empirical evidence has demonstrated that task performance requiring sustained attention is generally enhanced under warm-white lighting. Consequently, based on assessments specifically focused on sustained attention, it is recommended to implement lighting with a 6500 K color temperature in university learning environments [17]. *Creativity*, another cognitive function, is defined as the ability to produce or develop original work, theories, techniques, or thoughts [13]. Previous studies have highlighted the interaction effect between noise and heat on creativity [16]. Furthermore, the blue lighting color has been identified as a condition that enhances creativity [18]. In contrast, results of another study reported better performance in the verbal creative task under 3000 K compared to the 6000 K condition in a 300 lx environment [19].

In addition to cognitive functions, the level of *perceived comfort* is strongly associated with performance. Higher levels of perceived comfort are consistently linked to improved performance rates. [20]. When examining IEQ factors, the notion of comfort has predominantly focused on investigating physical and physiological sensations, as well as the subjective perception of specific elements, including ambient noise, temperature, lighting brightness/color, and Indoor Air Quality (IAQ) [21]. While research on IEQ factors' interaction effects has received increased attention over the last few decades in the fields of cognitive neuroscience and neurophysiology, the effect of IEQ factors' interaction on indoor environmental perception, including thermal comfort, acoustic comfort, visual comfort, and overall indoor environmental comfort, has not been comprehensively understood [22].

The perception of acoustic comfort is largely determined by variables such as noise level, noise type, and noise frequency. Recently, researchers have been discussing the interaction between acoustic and thermal conditions in relation to enhancing acoustic comfort [22]. These effects were identified in some of the previous experimental studies, demonstrating that the impact of increasing noise levels differs between warm and cold environments in terms of acoustic comfort [23]. On the other hand, Tiller et al. [24] reported that acoustic comfort votes were not affected by the ambient temperature [22]. In the realm of thermal comfort literature, thermal acceptability and thermal preference are frequently employed as metrics to evaluate the personal experience of thermal conditions in built environments [25]. Previous studies confirmed that thermal acceptability has a lower threshold than thermal comfort, as occupants might find the environment acceptable even if they do not feel completely comfortable [25], [26]. On the other hand, thermal preference involves gauging occupants' direct inclinations for modifying the thermal environment if they are in control. As a result, this concept finds extensive utility in personalized HVAC control systems that involve human input [25], [27]. Concerning thermal perception, a variety of findings are found in the literature. Thermal sensation, as another thermal comfort metric, was observed to be unaffected by noise [22], [28]. However, higher thermal comfort was reported in conditions with lower sound pressure levels (SPL) [29]. Additionally, previous research demonstrated that thermal perception is sensitive to CCT changes (5700 K vs. 2700 K) in both warm environments and cold environments, such that higher CCT could improve thermal comfort [30], [31]. While the results concluded from using different thermal-comfort metrics are inconsistent, it is expected that in the near thermal-neutral zone, the effect of temperature on acoustic comfort is relatively limited [32]. With regard to visual comfort, the effect of lighting CCT is unclear. While participants of a study evaluated the light in the 2700 K condition as warmer and dimmer and preferred the 2700 K over 5700 K in terms of color and brightness, their visual comfort did not significantly differ between the two CCTs [31]. Moreover, lighting color perception was observed to depend on room temperature [33]. Indoor environmental comfort, as an overall index to assess the physical indoor environment, can be driven by IEQ factors [22]. For instance, the thermal environment and acoustic environment were reported to have significant effects on overall comfort in certain seasons [34].

Furthermore, gender and Body Mass Index (BMI) can result in different IEQ perceptions that may affect cognitive functioning and perceived comfort [5], [35]. However, the findings of previous studies are inconsistent. For instance, women were reported to be more susceptible to temperature fluctuations [36], whereas another study found men to be more sensitive to temperature sensations in hot environments [28]. Additionally, while certain studies have suggested a limited impact of BMI on thermal sensation [37], the majority of previous research indicates that individuals with higher BMI tend to perceive environmental conditions as comparatively warmer than those with lower BMI [35].

The current body of research on interaction effects primarily focuses on two domains of IEQ, namely thermal and visual, thermal and acoustic, thermal and IAQ, and acoustic and visual [5]. However, the findings from these studies have been inconclusive and contradictory [5], [38]. Interactions involving three and more IEQ factors have not been explored comprehensively by utilizing both objective and subjective indicators of cognitive performance and comfort. Additionally, the moderation effect of individual differences (e.g., gender and BMI) on IEQ effects is unknown for most of the previously explored interactions. Essential physical environmental factors such as temperature, lighting color, and noise level have not been experimentally examined in terms of their combined effects on occupants' cognitive functioning and perceived comfort, to the best of our knowledge [5]. Built on this motivation, this study aims to investigate the cross-dimensional effects of background noise, air temperature, lighting CCT, gender, and BMI on cognitive functioning and perceived comfort. The main research questions of this study are:

- What are the interactive effects of air temperature, background noise, lighting CCT, gender, and BMI on attention and creativity as cognitive performance indicators?
- What are the interactive effects of air temperature, background noise, lighting CCT, gender, and BMI on the acoustic, thermal, and visual comfort of occupants?

METHODOLOGY

To examine the potential interaction effects of noise, lighting color, and temperature on various indicators of cognitive performance and perceived comfort, an experimental study was devised involving human subjects within a controlled environment. A mixed-design approach was employed to assess the potential interplay of different IEQ factors on attention, creativity, and comfort. Furthermore, to gain a deeper understanding of the relationships between objective cognitive performance and subjective perceived comfort, a correlation analysis was conducted.

Participants

Prospective participants were initially evaluated through a survey and subsequently excluded if they met any of the following criteria: visual impairment, color blindness, pregnancy, heart-related illnesses, wrist/hand injuries, or extreme sensitivity to fluctuating levels of lighting color, temperature, and noise. Participants' demographic information, along with their height and weight, was collected during this initial screening process. Eligible individuals were invited to participate in the experiment.

A total of 52 young adults (Avg=22.92, SD=3.64 years old) participated in the study, comprising an equal number of male and female college students who were all over 18 years of age. Participants' BMI (Avg=24.13, SD=5.41 kg/m^2) was categorized as healthy (n=39) or overweight/obese (n=13) if their BMI fell into ranges of [18.5-24.9] or [>25], respectively [32]. The sample size was determined based on a power analysis conducted using G*Power 3.1.9.7 software [39] and deemed to be adequate for achieving 80% power to detect within-between interactions in a factorial Analysis of Variance (ANOVA) test, with an effect size of f=0.17 and a significance level of α=0.05. As young students in university, participants might have different cognitive functioning and comfort perceptions regarding IEQ factors compared to the other demographic groups. Therefore, generalization of the results to larger populations should be carried out with caution [40].

Experimental Design

An experimental study approach in a controlled environment was chosen to ensure identical test conditions for participants in each experimental group. A 2 (temperature levels) × 2 (noise levels) × 2 (lighting CCT levels) mixed-subjects design was implemented, where the lighting CCT and noise level were within-subject factors, and the temperature was a between-subject factor. In each of the experimental groups, the temperature was kept constant, while the four within-subject measures differed in either noise level or lighting CCT. The order of the four environmental conditions across the participants of each group was randomized using a Latin square design [41]. The simultaneous examination of objective cognitive performance metrics and subjective comfort within the context of varying acoustic, thermal, and visual conditions represent a pioneering approach in this field of study. However, it is important to acknowledge that certain limitations were encountered in experimental design. IEQ factors are not limited to temperature, lighting color, and noise level [42]. However, considering more than three factors involves statistical complexities and requires much larger sample sizes, which can be facilitated by allocating proper incentives in future studies.

Experimental Conditions

To emulate the acoustic environment of an open-plan office, we chose to incorporate background speech noise levels of 50 dB and 65 dB. These particular noise levels were selected based on prior research that has demonstrated their efficacy in inducing performance hindrance and discomfort, respectively [43]–[45]. To minimize ambient noise during the study, the Bose QuietComfort 35 headphones were employed for provisioning both noise conditions [46]. To generate the background noise, crowd-talking noise was selected, which was produced by the Soundjay platform [47], [48]. Decibel levels were measured with a BAFX digital sound meter [49]. To replicate the thermal environment found in office settings, temperatures of 25°C (77°F) and 20°C (68°F) were chosen, as representatives of warm and cool indoor thermal conditions, respectively. These temperature setpoints fall within the range reported in previous studies conducted in California [50], while the recommended and actual cooling and heating setpoints vary with respect to geographical location, climatic condition, and building properties [51]–[54]. For thermal comfort purposes, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommends that temperature could range between 19 and 28 °C [55], [56]. Moreover, the California Department of General Services recommends winter setpoints no higher than 20 °C and summer setpoints no lower than 25.6 °C, except in cases where specific job requirements may pose health and safety risks [57]. Similarly, the Occupational Safety and Health Administration

(OSHA) suggests temperature control in the range of 20-24°C, along with humidity control between 20% and 60% [58]. Furthermore, the Pacific Energy Center considers the comfort zone to be within the range of 20-27°C in California [59]. The chosen setpoints have also been explored as thresholds for defining overly cold (<20 °C) or excessively warm (>25.6 °C) conditions in educational settings in California [60]. Additionally, previous research indicates that adjusting the cooling setpoint to 25 °C and the heating setpoint to 20 °C can yield significant energy-saving benefits without compromising satisfaction levels [61]. Taking into account the existing literature and guidelines, we chose temperatures of 25°C and 20°C to realistically replicate the indoor environmental stressors while ensuring they fall within realistic ranges. Pro1 Model T771 was used to set the thermal set points [62]. Participants were asked to wear single-layer clothing. IAQ factors including CO_2 level, Particulate Matter (PM) 2.5, and Total Volatile Organic Compounds (TVOC) were collected via the Awair Omni sensor [63]. The descriptive statistics of these factors across cool and warm thermal settings is provided in **Table 1**.The significance of IAQ factors across two thermal settings was tested and the results of covariate analysis are provided in the Appendix C. Also relative humidity was within the 36%-41% range across all the environmental conditions. Regarding lighting CCT, 2700 K and 6500 K were chosen as two common representatives of warm and cool lighting colors, respectively [64]. To prepare lighting CCT conditions, four floor lamps equipped with Torkase 10W Smart Light Bulbs were utilized [65].

Table 1. The average and standard deviation of IAQ factors in the cool and warm thermal settings

Thermal Settings	IAQ factors		
	CO_2 (ppm)	PM 2.5 ($\mu g/m^3$)	TVOCs (ppb)
Cool	740 (±88)	0.77 (±16)	227 (±100)
Warm	813 (±110)	1.44 (±45)	528 (±365)

The experiment took place in a student office in Los Angeles, having a North American Mediterranean climate, where there were no additional environmental stimuli other than the defined environmental setpoints. The room had no natural daylight. Apart from the controlled environmental conditions, the eye-level illuminance level was 225 lux (±10). **Figure 1** depicts a sample view of the experimental setting. Although the experimental setting enabled us to control the variables and monitor the effects of interventions carefully, it represents one type of office space, and additional caution should be taken while generalizing to the various types of offices (e.g., shared offices with windows, private offices, etc.) [5].

Figure **1.** Experimental setting

Measurements

Cognitive performance tests include the Stroop test, continuous performance test (CPT), and remote associates test (RAT) to assess selective attention, sustained attention, and creativity. The range of Estimated Marginal Mean (EMM) for the accuracy of cognitive performance indicators was [0-1] (0: the lowest accuracy, 1: the highest accuracy). The perceived environmental comfort involved acoustic comfort, thermal comfort, visual comfort, and overall comfort, all assessed by the subjective votes of participants.

Cognitive performance tests

Stroop Test: The Stroop test is a well-established measure of selective attention, representing an individual's capacity to overcome a previously learned response [66]. During the test, participants were presented with 120 colored words, including the names of four colors (red, green, blue, and yellow), in either a consistent or inconsistent ink color. For instance, the word "blue" might be printed in green ink. Half of the 120 trials displayed color words in a consistent ink color, while the other half presented color words in an inconsistent ink color. Each word was presented on the screen for one second, followed by a blank screen for another second before the next colored word appeared. Participants were required to press the corresponding color-labeled keystroke based on the ink color they perceived, indicating the ink, not the color associated with the nature of the word. Colored pieces of paper covered each number key to facilitate this association. The incorrect response was defined as either failing to respond within two seconds or pressing the wrong key. To prevent any learning effect across subsequent experimental conditions of the test, the order of the trials was randomized [67].

CPT: CPT is a type of assessment that measures an individual's sustained attention and concentration [13]. In our study, a version of the CPT was used that consisted of 16 stimuli created by combining four shapes (star, circle, square, and triangle) with four colors (yellow, red, white, and blue). Participants were shown a total of 320 stimuli on the screen, each appearing for 0.3 seconds and followed by a one-second inter-stimulus interval before the next stimulus was presented. Participants were instructed to press the "Enter" keystroke only if they saw a "red star," which was the designated target stimulus. If a participant failed to respond within the allotted time or pressed the keystroke when a non-target stimulus appeared, the response was marked as incorrect. The target stimulus, color-conjunctive distractors (red non-star), shape-conjunctive distractors (non-red star), and non-conjunctive distractors (non-red and non-star) accounted for

30%, 17.5%, 17.5%, and 35% of all trials, respectively. To minimize any potential learning effect, the order of stimulus presentation was randomized [67].

RAT: Remote association is a link between one item in a list or series and another item that does not adjoin it [13]. In the present study, the RAT was used to measure creativity by assessing an individual's ability to make connections between words that are not directly adjacent to each other [10], [68]. Participants were presented with three words on the screen and asked to generate a fourth word that was conceptually related to the other three cues, such as the words "cream," "skate," and "water" being linked by the word "ice." The word bank used in the study was compiled from previously published research [69]. Ten trials were conducted without time constraints, and each set of words had a single correct answer. Accuracy scores were calculated based on the number of correct answers obtained out of ten trials for each experimental condition. There were no identical triplets among all the word sets presented to each participant.

***Environmental Comfort Votes*:** Four surveys were conducted to solicit participants' subjective evaluations of their comfort levels pertaining to noise, temperature, lighting color, and overall environmental conditions. To accurately quantify participants' comfort levels, a five-point Likert scale was utilized, which is widely employed in IEQ studies [70]. The scale ranged from one to five, indicating "very uncomfortable," "slightly uncomfortable," "neither uncomfortable nor comfortable," "slightly comfortable," and "very comfortable," respectively. The questions included in the surveys were selected based on prior scientific publications [71]–[73] and guidelines [7]. For each IEQ comfort domain, the average of corresponding votes collected in the four surveys was considered for analysis.

Procedure

Upon arrival at the study location, participants were presented with informed consent and subsequently gave their consent to participate in the experiment. The Institutional Review Board (IRB) of the University of Southern California approved the study, and all relevant guidelines and regulations were adhered to throughout the entire experimental procedure. Participants were given the option to withdraw from the experiment at any point.

The experimental session commenced with a briefing on the experiment, including instructions on the tasks to be performed. Subsequently, participants underwent a training session to familiarize themselves with the computer tasks and clarify any questions or issues before beginning the experiment. Four combinations of noise and light conditions were presented to participants for each thermal condition (between-subject factor), as illustrated in **Figure 2**. Participants completed three computer-based tasks in a predetermined sequence for each experimental condition (**Figure 2**). The sequence of tasks was standardized, starting with the Stroop test, followed by the CPT, and concluding with the RAT. The Psychopy software version 2022.2.4 [74] was employed to administer all tests, and participants' performance was evaluated based on their accuracy. At the beginning of each condition, participants were asked to rate their perceived comfort (IEQ survey) regarding the acoustic, thermal, visual, and overall. The entire experiment's duration was approximately 135 minutes. As a typical experimental study, the duration of exposure to environmental stressors was short, which might be significantly less than the real working/studying hours of young adults and office workers [75]. Additionally, it should be noted that the exposure duration time might affect the IEQ interaction effects on occupants' cognitive functioning and perceived comfort [31], while some studies reported that the effect of IEQ factors on cognitive functioning has some lagged effects [75]. The experiments were conducted using HP Pavilion Desktop TP01 [76].

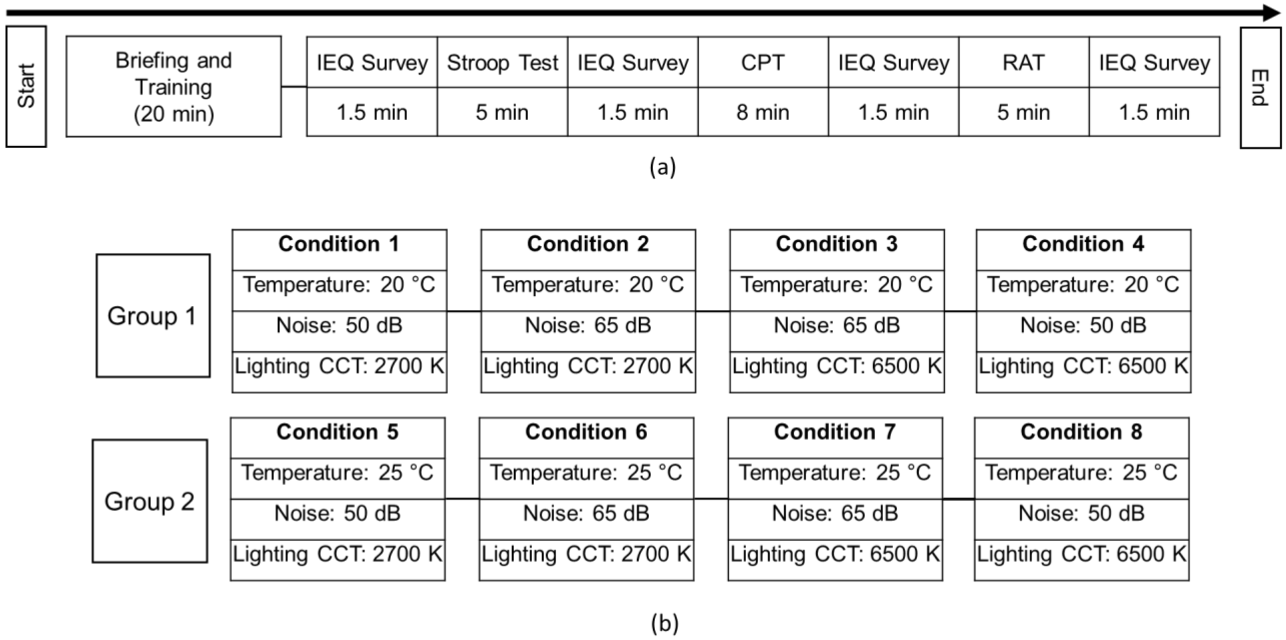


Figure 2. An overview of experimental design: **(a)** procedure, **(b)** environmental conditions

Analysis

The statistical analysis employed a repeated-measures analysis of covariance (ANCOVA) to investigate the research questions. A 2 (noise level: 50 dB or 65 dB) × 2 (lighting CCT: 2700 K or 6500 K) × 2 (temperature: 20°C or 25°C) was designed. To examine the potential impact of gender (female or male) and BMI status (healthy or overweight/obese), additional analyses were conducted by including these variables as between-subject factors in conjunction with temperature. The dependent variables in the repeated measures ANCOVA included both objective performance indicators (accuracy) and subjective comfort ratings regarding IEQ factors. The significance level was set at 0.05, and the marginal significance level was set at 0.10. For selective attention, four participants were removed from the analysis since their scores in the first condition were considered outliers, more likely because of insufficient dedicated attention in the training session of the experiment and, thus, failure to perform properly as the experiment started. Additionally, bivariate correlation analysis was conducted to explore correlations between subjectively perceived comfort votes and objective cognitive performance indicators. The significance level for correlation analysis was set at 0.05. All the data analysis was conducted using the SPSS 28 software [77].

RESULTS AND DISCUSSION

This section outlines the results of the statistical analysis, including the main and interaction effects of noise level, lighting CCT, temperature, gender, and BMI on each dependent variable (i.e., selective attention, sustained attention, creativity, acoustic comfort, thermal comfort, visual comfort, and overall comfort). The significance of the examined effects exhibits variation across all the variables under investigation. Notably, the findings related to the three-way interactions contribute novelty to the existing literature. Concerning two-way interactions, the current study's outcomes both replicate certain earlier investigations and contradict others, thus aligning with the prevailing inconsistencies found in prior scholarly works. The descriptive statistics, including the mean and standard deviation of the cognitive performance indicators and comfort votes, are presented in Appendix A.

Cognitive functions

Selective attention

The results show no significant main effect of lighting CCT, temperature, noise, gender, or BMI on participants' selective attention assessed by the response accuracy in the Stroop test. However, the significance of interaction effects was considerable (**Table 2**).

Table 2. Effects of IEQ factors and individual differences on selective attention

Tests of Within-Subjects Contrasts				
Effect	df	F	p	η^2
Noise	1,46	0.056	0.814	0.001
Noise × Temperature †	1,46	**2.875**	**0.097**	**0.059**
Lighting CCT	1,46	0.243	0.624	0.005
Lighting CCT × Temperature †	1,46	**3.390**	**0.072**	**0.069**
Noise × Lighting CCT	1,46	0.131	0.719	0.003
Noise × Lighting CCT × Temperature	1,46	0.459	0.501	0.010
Noise × Gender	1,44	0.838	0.365	0.019
Noise × Temperature × Gender	1,44	0.010	0.922	0.000
Lighting CCT × Gender	1,44	0.004	0.951	0.000
Lighting CCT × Temperature × Gender	1,44	2.178	0.147	0.047
Noise × Lighting CCT × Gender *	1,44	**6.351**	**0.015**	**0.126**
Noise × Lighting CCT × Temperature × Gende	1,44	1.121	0.296	0.025
Noise × BMI	1,44	0.009	0.926	0.000
Noise × Temperature × BMI	1,44	0.441	0.510	0.010
Lighting CCT × BMI	1,44	0.022	0.881	0.001
Lighting CCT × Temperature × BMI	1,44	0.076	0.784	0.002
Noise × Lighting CCT × BMI	1,44	0.182	0.672	0.004
Noise × Lighting CCT × Temperature × BMI *	1,44	**5.466**	**0.024**	**0.110**
Tests of Between-Subjects Effects				
Effect	df	F	p	η^2
Temperature	1,46	0.691	0.410	0.015
Gender	1,44	0.657	0.422	0.015
Temperature × Gender	1,44	0.138	0.712	0.003
BMI	1,44	0.441	0.510	0.010
Temperature × BMI	1,44	1.156	0.288	0.026

*: $p < 0.05$, †: $0.05 < p < 0.10$

With regard to selective attention, a marginally significant interaction effect was observed between noise and temperature ($F_{1,46} = 2.875$, $p = 0.097$, $\eta_p^2 = 0.059$), indicating that the impact of temperature on selective attention scores was moderated by the level of noise (**Table 2**). Specifically, under high noise conditions, the average selective attention score was lower in the warm temperature compared to the cool temperature ($M_{65dB,25°C}$=0.925 vs. $M_{65dB,20°C}$=0.941), while under low noise conditions, the lowering effect of higher temperature was relatively minimal ($M_{50dB,25°C}$=0.931 vs. $M_{50dB,20°C}$=0.933) (**Figure 3a**). Clinical research provided evidence of significant activation in the cingulate cortex and dorsolateral prefrontal cortex while doing attention-involving tasks [78]. Given that high noise levels and high temperatures can impair cognitive functioning and decrease attention by reducing the prefrontal cortex's ability to process information [79], [80], the observed interaction between noise and temperature is explainable from a physiological perspective. As reviewed by Hygge and Knez, there exists evidence suggesting an interaction between noise and temperature within the range of [20°C-30°C] and acoustic conditions spanning [37dB-85dB]. This suggests that, in the context of attentional tasks, a moderate rise in temperature can potentially counterbalance an increased noise level. However, Hygge and Knez could not identify any evidence for the interplay between noise and elevated temperatures beyond the aforementioned parameters [16]. Given that temperatures exceeding 30°C and noise levels surpassing 85dB are atypical scenarios in office environments, the absence of studies addressing this noise and temperature interaction within these environmental conditions can be reasonably understood.

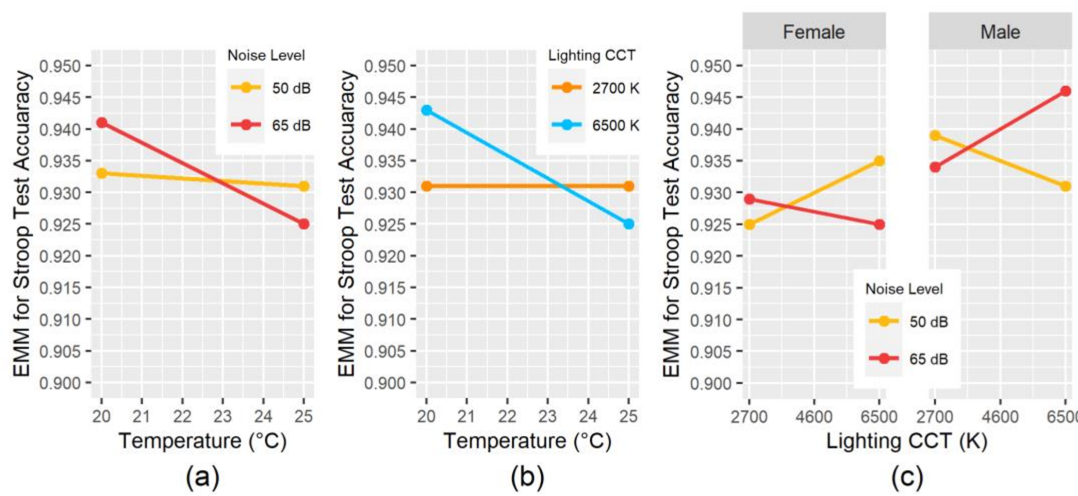


Figure 3. Effects of IEQ factors and individual differences on Stroop test response accuracy: **(a)** noise × temperature interaction, **(b)** lighting CCT and temperature interaction, **(c)** lighting CCT × noise × gender interaction

Furthermore, a marginally significant lighting CCT × temperature interaction effect ($F_{1,46} = 3.390$, $p = 0.072$, $\eta_p^2 = 0.069$) was found (**Table 2**). In the 6500 K lighting condition, the warm temperature led to a noticeably lower selective attention score ($M_{6500K,25°C}$=0.925) compared to the cool temperature ($M_{6500K,20°C}$=0.943), whereas, in the 2700 K lighting condition, the temperature had no effect on selective attention scores ($M_{2700 K, 25°C}$=0.931 vs. $M_{2700 K,20°C}$=0.931) (**Figure 3b)**. This reveals some evidence of the lighting CCT effect, such that participants performed better under the cool lighting (6500 K) condition. This is aligned with previous studies indicating that high CCT enhances attention [81].

When considering gender as a between-subject factor, a significant lighting CCT × noise × gender three-way interaction effect was observed ($F_{1,44} = 6.351,\ p = 0.015,\ \eta_p^2 = 0.126$) (**Table 2**). The impact of lighting CCT and noise varied for these two gender groups. Specifically, among male participants, higher CCT led to better performance when exposed to high levels of noise ($M_{2700K,65dB,male}$=0.934 vs. $M_{6500K,65dB,male}$=0.946), while among female participants, higher CCT resulted in poorer performance in the same acoustic environment compared to the condition with lower CCT ($M_{2700K,65dB,female}$=0.929 vs. $M_{6500K,65dB,female}$=0.925). Conversely, under low noise conditions, higher CCT led to higher scores among females ($M_{6500K,50dB,female}$=0.925 vs. $M_{2700K,50dB,female}$=0.935) but lower scores among male participants compared to the condition with lower CCT ($M_{6500K,50dB,male}$=0.939 vs. $M_{2700K,50dB,female}$=0.931) (**Figure 3c**). These findings are consistent with previous research emphasizing the influential role of lighting CCT on cognitive processes. Specifically, exposure to cooler CCT light has been associated with improvements in attentional performance [14], with possible differences observed between genders [82]. Additionally, another study reported that CCT levels affected the attention of females. For female subjects, the performance metrics were lower for the 6500 K subgroup than those within the 2700 or 4300 K subgroups [64], whereas, in our study, noise moderated the interaction effect between lighting CCT and gender. Finally, given the complex nature of our experiment design, an inscrutable four-way interaction between noise, lighting, temperature, and BMI ($F_{1,44} = 5.466,$ $p = 0.024,\ \eta_p^2 = 0.110$) was noted (**Table 2**).

Sustained attention

No significant main effect of lighting CCT, temperature, noise, gender, or BMI was found on participants' sustained attention assessed by the continuous performance test. Based on neuroscientific studies, the connections between the motor cortex, occipital lobes, and the cerebellum were primarily predictors of better sustained attention [83]. While some of the authors reported that the lighting condition did not impact performance on the sustained attention task [84], some others reported improvements under higher CCT values or blue-enriched lights, which was associated with several mechanisms, including lowering alpha-band activity, increasing melatonin suppression, and/or restoring diminished attentional resources in a three-week study [85]. The later study explored the effect of lighting CCT on sustained attention in a relatively long period using 6500K and 17000K lighting conditions. Given the absence of such an effect in the conducted study, it can be inferred that sustained attention is more likely to be affected by cool lighting CCT when occupants are under prolonged lighting exposure. On the other hand, another experiment pointed out that medium levels of lighting CCT (e.g., 4300 K) could benefit sustained attention more while assessing under nine lighting conditions, each continued for 4.3 min [86]. This effect was observed comparing 4300K, 3300K, and 5300K in three different lighting brightness conditions (300lx, 500 lx, and 750lx). While different lighting CCT conditions can solely drive the significance of their effect on sustained attention, it can also be deduced that the lighting brightness may moderate the effect of lighting CCT on sustained attention. Additionally, the absence of temperature's effect on sustained attention can be related to exposure duration since increased temperatures only tended to increase errors in the performance of sustained mental tasks that continued for 60 min or longer [87], [88].

Creativity

Table 3 summarizes the statistical parameters concerning all the possible main and interaction effects of IE factors, gender, and BMI on creativity assessed by RAT.

Table 3. Effects of IEQ factors and individual differences on RAT response accuracy

Tests of Within-Subjects Contrasts				
Source	df	F	p	η^2
Noise	1,50	0.257	0.614	0.005
Noise × Temperature	1,50	0.257	0.614	0.005
Lighting CCT	1,50	0.302	0.585	0.006
Lighting CCT × Temperature	1,50	0.302	0.585	0.006
Noise × Lighting CCT **	**1,50**	**10.868**	**0.002**	**0.179**
Noise × Lighting CCT × Temperature	1,50	0.719	0.401	0.014
Noise × Gender	1,48	0.384	0.539	0.008
Noise × Temperature × Gender †	**1,48**	**3.453**	**0.069**	**0.067**
Lighting CCT × Gender	1,48	0.428	0.516	0.009
Lighting CCT × Temperature × Gender	1,48	0.761	0.387	0.016
Noise × Lighting CCT × Gender	1,48	0.317	0.576	0.007
Noise × Lighting CCT × Temperature × Gender	1,48	1.267	0.266	0.026
Noise × BMI	1,48	1.850	0.180	0.037
Noise × Temperature × BMI	1,48	0.016	0.899	0.000
Lighting CCT × BMI	1,48	0.862	0.358	0.018
Lighting CCT × Temperature × BMI	1,48	2.001	0.164	0.040
Noise × Lighting CCT × BMI	1,48	1.256	0.268	0.025
Noise × Lighting CCT × Temperature × BMI *	**1,48**	**8.090**	**0.007**	**0.144**
Tests of Between-Subjects Effects				
Effect	df	F	p	η^2
Temperature	1,50	0.356	0.553	0.007
Gender †	**1,48**	**3.167**	**0.081**	**0.062**
Temperature × Gender	1,48	0.000	1.000	0.000
BMI	1,48	0.056	0.813	0.001
Temperature × BMI	1,48	0.155	0.696	0.003

**: $p < 0.01$, *: $p < 0.05$, †: $0.05 < p < 0.10$

A marginally significant main effect of gender was found on participants' creativity assessed by RAT ($F_{1,48} = 3.167$, $p = 0.081$, $\eta_p^2 = 0.062$) (**Table 3**); on average, such that female participants got higher scores (M_{female}=0.482) than male participants (M_{male}=0.374) (**Figure 4a**). The impact of gender on remote association skills is moderated by a marginally significant noise × temperature × gender interaction effect ($F_{1,48} = 3.453$, $p = 0.069$, $\eta_p^2 = 0.067$) (**Table 3**), as shown in **Figure 4b**. Specifically, in the cool temperature, exposure to the high noise level had a positive effect on female participants' creativity ($M_{65dB,20°C,female}$=0.512) compared to low noise levels ($M_{50dB,20°C,female}$=0.488), while male participants were less creative while being exposed to high noise level ($M_{65dB,20°C,male}$=0.381 vs. $M_{50dB,20°C,male}$=0.404). Conversely, in the warm temperature, low noise level had a positive effect on female participants' creativity compared to high noise level ($M_{50dB,25°C,female}$=0.477 vs. $M_{65dB,25°C,female}$=0.477), whereas male participants performed better in the high noise level ($M_{65dB,25°C,male}$=0.388) compared to the low noise level

($M_{50dB,25°C,male}$=0.323). Prior studies have documented an interaction effect between noise and temperature on a creativity test [89]. However, our study extends these findings by demonstrating that the interaction effect between noise and temperature on creativity is subject to gender moderation. Furthermore, our results indicated that females performed better in the creativity test.

Regarding the main effect of noise, our analysis revealed that an environment with a noise level of 65 dB exhibited superior performance compared to 50 dB, on average (M_{65dB}=0.433 vs. M_{50dB}=0.423) **(Table 3)**. Previous research has documented that higher levels of noise can induce distraction, leading to an elevated construal level and abstract processing, thereby enhancing creativity [1]. However, contrasting results were found in another study [67], where under white noise conditions, there was no significant difference in creativity between 65 dB and 45 dB. This discrepancy could be attributed to the nature of the noise type and its specific impact on participants' cognitive functions [23]. Many studies reported that some noise types, such as white noise, might facilitate cognitive abilities via stochastic resonance based on internal neural noise (a fundamental mechanism that contributes to moderate brain arousal) [90], [91]. However, some other noise types, such as crowd talking or traffic noise, could be more disturbing [92] and thus may hinder creativity capabilities.

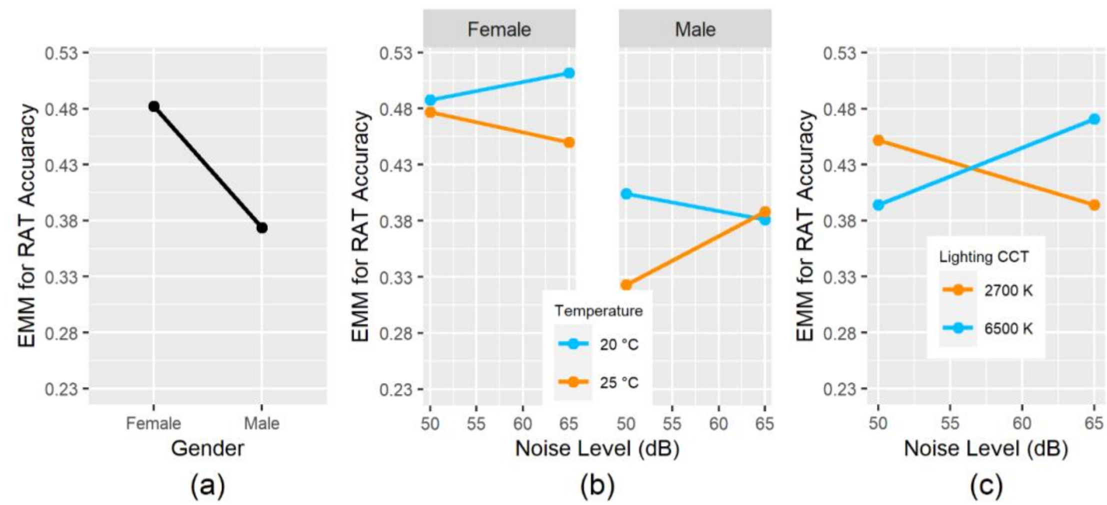


Figure 4. Effects of IEQ factors and individual differences on RAT response accuracy: **(a)** effect of gender, **(b)** gender × noise × temperature interaction effect, **(c)** noise × lighting CCT interaction effect

Furthermore, a significant noise × lighting CCT interaction effect ($F_{1,50} = 10.868$, $p = 0.002$, $\eta_p^2 = 0.179$) (**Table 3**) was noted, as also shown in **Figure 4c**. This indicates that in high lighting CCT conditions, participants scored higher on creativity tasks when exposed to the high noise level ($M_{65dB,6500K}$=0.471) compared to the low noise level ($M_{50dB,6500K}$=0.394). Conversely, in low lighting CCT conditions, participants scored higher on creativity tasks when exposed to the low noise level ($M_{50dB,2700K}$=0.452) compared to the high noise level ($M_{65dB,2700K}$=0.394). This is a novel finding, and no related support was found in previous literature. Creativity, being a complex cognitive ability, can engage various regions of the brain. For example, verbal creativity primarily relies on the left hemisphere and involves specific areas such as the left middle frontal gyrus, insula, and cerebellum [93]. Given the complexity of creativity, it is hard to link IEQ variations to the changes in specific parts of the brain while doing creativity-involved tasks. Finally, there was an inscrutable four-way interaction between noise, lighting CCT, temperature, and BMI ($F_{1,48} = 8.090,\ p = 0.007,\ \eta_p^2 = 0.144$) (**Table 3**).

Environmental Comfort

The participants' subjective votes for perceived comfort regarding thermal, acoustic, and visual aspects of the environment were examined under varying noise, lighting CCT, temperature, gender, and BMI levels. The descriptive statistics for each dependent variable in each experimental condition are provided in Appendix B. All the main and significant effects are summarized in **Table 4**.

Table 4. Effects of IEQ factors and individual differences on perceived comfort

Tests of Within-Subjects Contrasts													
Dependent Variable		Acoustic Comfort			Thermal Comfort			Visual Comfort			Overall Comfort		
Effects\Statistical Parameters	df	F	sig.	η2	F	p	η2	F	p	η2	F	p	η2
Noise	1,50	**47.916**	**<.001 *****	**0.489**	0.111	0.740	0.002	0.193	0.662	0.004	**10.486**	**0.002 ****	**0.173**
Noise × Temperature	1,50	**5.140**	**0.028 ***	**0.093**	0.045	0.833	0.001	1.209	0.277	0.024	0.300	0.586	0.006
Lighting CCT	1,50	0.338	0.564	0.007	0.715	0.402	0.014	**3.731**	**0.059 †**	**0.069**	0.673	0.416	0.013
Lighting CCT × Temperature	1,50	1.181	0.282	0.023	0.512	0.478	0.010	0.213	0.647	0.004	0.419	0.520	0.008
Noise × Lighting CCT	1,50	**7.013**	**0.011 ****	**0.123**	0.189	0.665	0.004	0.035	0.853	0.001	**3.864**	**0.055 †**	**0.072**
Noise × Lighting CCT × Temperature	1,50	**5.936**	**0.018 ***	**0.106**	0.021	0.885	0.000	0.993	0.324	0.019	1.328	0.255	0.026
Noise × Gender	1,48	0.000	0.984	0.000	0.008	0.929	0.000	1.224	0.274	0.025	0.022	0.884	0.000
Noise × Temperature × Gender	1,48	0.327	0.570	0.007	0.321	0.573	0.007	1.392	0.244	0.028	0.194	0.662	0.004
Lighting CCT × Gender	1,48	**2.921**	**0.094 †**	**0.057**	1.215	0.276	0.025	**9.142**	**0.004 ****	**0.160**	**3.928**	**0.053 †**	**0.076**
Lighting CCT × Temperature × Gender	1,48	0.006	0.939	0.000	0.449	0.506	0.009	0.115	0.736	0.002	0.095	0.759	0.002
Noise × Lighting CCT × Gender	1,48	0.438	0.511	0.009	0.007	0.932	0.000	0.136	0.714	0.003	0.220	0.641	0.005
Noise × Lighting CCT × Temperature × Gender	1,48	0.273	0.604	0.006	0.007	0.932	0.000	0.456	0.503	0.009	0.542	0.465	0.011
Noise × BMI	1,48	0.372	0.545	0.008	0.039	0.845	0.001	0.241	0.625	0.005	0.710	0.404	0.015
Noise × Temperature × BMI	1,48	1.338	0.253	0.027	1.133	0.292	0.023	**3.594**	**0.064 †**	**0.070**	0.812	0.372	0.017
Lighting CCT × BMI	1,48	1.701	0.198	0.034	1.981	0.166	0.040	0.108	0.744	0.002	0.534	0.468	0.011
Lighting CCT × Temperature × BMI	1,48	0.540	0.466	0.011	**5.173**	**0.027 ***	**0.097**	1.670	0.202	0.034	1.561	0.218	0.031
Noise × Lighting CCT × BMI	1,48	0.105	0.747	0.002	0.277	0.601	0.006	**3.099**	**0.085 †**	**0.061**	**3.546**	**0.066 †**	**0.069**
Noise × Lighting CCT × Temperature × BMI	1,48	0.001	0.969	0.000	0.986	0.326	0.020	1.404	0.242	0.028	1.055	0.309	0.022
Tests of Between-Subjects Effects													
Dependent Variable		Acoustic Comfort			Thermal Comfort			Visual Comfort			Overall Comfort		
Effects\Statistical Parameters	df	F	p	η2	F	p	η2	F	p	η2	F	p	η2
Temperature	1,50	**3.601**	**0.064 †**	**0.067**	**10.305**	**0.002 ****	**0.171**	0.804	0.374	0.016	**3.576**	**0.064 †**	**0.067**
Gender	1,48	**3.819**	**0.057 †**	**0.074**	0.093	0.761	0.002	0.302	0.585	0.006	0.203	0.655	0.004
Temperature × Gender	1,48	0.193	0.662	0.004	1.077	0.305	0.022	2.237	0.141	0.045	1.401	0.242	0.028
BMI	1,48	0.840	0.364	0.017	0.144	0.706	0.003	0.017	0.896	0.000	0.602	0.442	0.012
Temperature × BMI	1,48	0.053	0.819	0.001	1.891	0.176	0.038	1.898	0.175	0.038	0.302	0.585	0.006

***: p < 0.001, **: p < 0.01, *: p < 0.05, †: 0.05 < p < 0.10

Acoustic comfort

As summarized in **Table 4**, noise had a main effect ($F_{1,50} = 47.916,\ p =< 0.001,\ \eta_p^2 = 0.489$) on acoustic comfort, such that participants were more comfortable at the lower noise level (M_{50dB}=3.382) compared to the high noise level (M_{65dB}=2.553). The anticipation of increased comfort levels in response to reduced ambient noise amidst crowd conversation has been substantiated and fortified by prior research findings [23], [34]. Nevertheless, it is important to acknowledge that the sound type can potentially alter the observed outcomes. This is exemplified by the scenario wherein a musical auditory setting, despite exhibiting similar SPL as a noisy environment, actually elicits a greater sense of acoustic comfort [32]. Additionally, the marginally significant effect of temperature ($F_{1,50} = 3.601,\ p = 0.064,\ \eta_p^2 = 0.067$) was observed in a way that the warm temperature led to higher comfort rates ($M_{25°C}$=3.216) compared to the cool temperature ($M_{20°C}$=2.719), which is in line with the findings of another study [34]. Additionally, a significant noise × temperature interaction ($F_{1,50} = 5.140,\ p = 0.028,\ \eta_p^2 = 0.093$) was noted, which qualified their main effects. As depicted in **Figure 5a**, this effect indicates that in the high noise level, warm temperature led to a considerable drop in acoustic comfort compared to the cool temperature ($M_{65dB,25°C}$=2.938 vs. $M_{65dB,20°C}$=2.168), whereas the temperature was less likely to affect the acoustic comfort rates when they were exposed to low noise level ($M_{50dB,25°C}$=3.495 vs. $M_{50dB,20°C}$=3.269). While the interaction effect of noise and temperature on acoustic comfort has been reported in several studies [22], some of the studies limited this effect only to specific types of noises [28] or reported it as slight or none [32], [94].

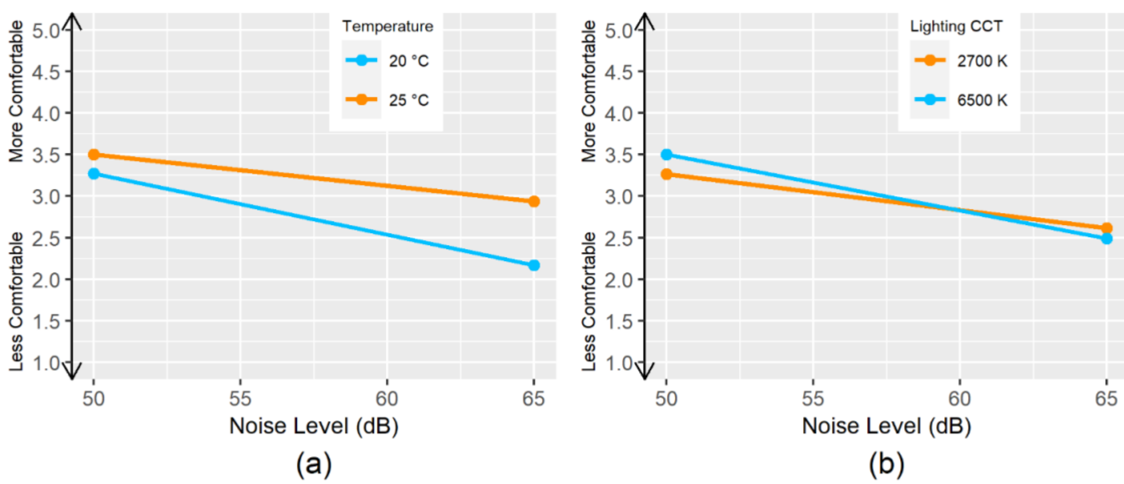


Figure 4. Interaction effects of IEQ factors on acoustic comfort: **(a)** noise × temperature interaction, **(b)** noise × lighting CCT interaction

Additionally, the main effect of noise was moderated by its significant interaction with lighting ($F_{1,50} = 7.013,\ p = 0.011,\ \eta_p^2 = 0.123$) in **Table 4**, as also illustrated in **Figure 5b**. During exposure to the low noise level, participants were more likely to be satisfied with higher lighting CCT compared to lower lighting CCT ($M_{50dB,6500K}$=3.500 vs. $M_{50dB,2700\ K}$=3.264), whereas when participants were exposed to the high noise level, higher comfort rates were more likely associated with lower lighting CCT compared to higher lighting CCT ($M_{65dB,6500K}$=2.615 vs. $M_{65dB,2700K}$=2.490). While the related comfort studies are limited, some studies found that lighting CCT had no influence on noise annoyance in a medium brightness condition, while the interaction between lighting CCT and noise level affected noise annoyance [95]. Moreover, it was noted that gender had a marginally significant effect ($F_{1,48} = 3.819,\ p = 0.057,\ \eta_p^2 = 0.074$) (**Table 4**) on acoustic comfort in a way that females were more comfortable with the acoustic environment than males (M_{female}=3.219 vs. M_{male}=2.716), regardless of the noise level. Finally, given the complex nature of our experiment design, there was also an inscrutable significant interaction effect of noise × lighting CCT × temperature ($F_{1,50} = 5.936,\ p = 0.018,\ \eta_p^2 = 0.106$) (**Table 4**).

Thermal comfort

The temperature had a main effect on thermal comfort ($F_{1,50} = 10.305,\ p = 0.002,\ \eta_p^2 = 0.171$), such that participants were more comfortable with the warm temperature ($M_{25°C}$=3.846) compared to the cool temperature ($M_{20°C}$=2.969). However, no significant interaction effect of temperature and noise on thermal comfort was found in our study. The combined effects of acoustic and thermal conditions on human perception have not been clearly understood yet. Previous studies have indicated that human perception of thermal comfort tends to be in a neutral range when considering temperature and noise. These studies found that thermal sensation remained unchanged despite variations in noise levels (ranging from 45 to 65 dB) and temperatures (ranging from 18°C to 30°C), even when the relative humidity and type of noise were altered [28]. In contrast, the effect of noise on thermal comfort was reported in some of the earlier studies. For instance, under four temperatures within [19°C-28°C] and five noise levels within [46.6 dB-95.5dB], thermal comfort and discomfort significantly decreased and increased respectively with increasing the noise level. It can be inferred that higher levels of noise, such as 95.5 dB, can disturb the neutral zone of perceived thermal comfort and thus cause additional discomfort. In this regard, Nagano and Horikoshi relied on the fact that thermal comfort, as a wide connotation, also includes physiological and psychological aspects, and different noise levels could have different effects on subjects' emotions and could further affect thermal comfort [23], [29]. While experimental conditions can be influenced by factors like climate conditions, regional preferences, and building operational constraints, these varying conditions across relevant studies complicate comparisons between them. Furthermore, it is important to acknowledge that the interplay between noise and temperature might also be contingent on the specific type of noise.

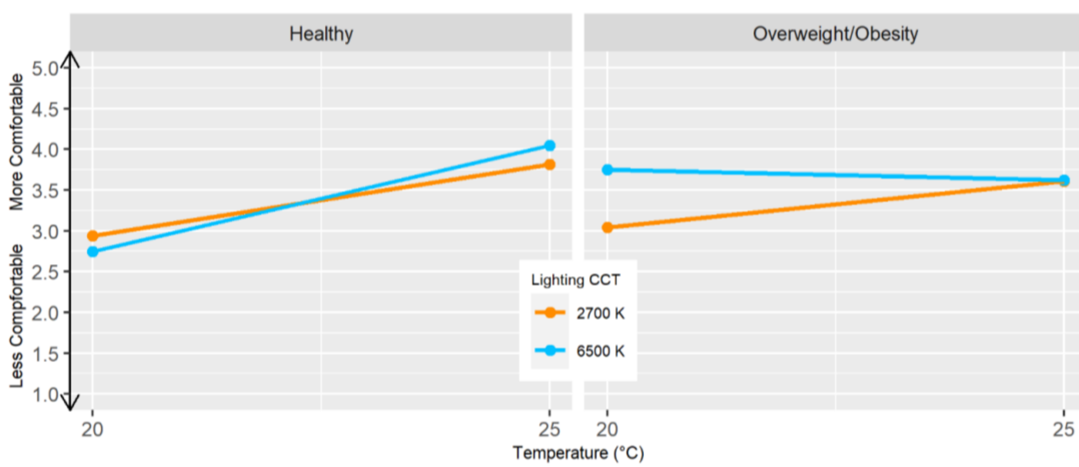


Figure 5. Interaction effects of IEQ factors on thermal comfort

Additionally, a significant interaction effect between temperature × lighting CCT × BMI ($F_{1,48} = 5.173,\ p = 0.027,\ \eta_p^2 = 0.097$) (**Table 4**) was observed such that the BMI status of participants affected the interaction effect between lighting CCT and temperature. As presented in **Figure 6**, among participants with overweight/obese BMI, it was less likely that lighting CCT changed the perceived thermal comfort in the warm temperature ($M_{25°C,2700K,overweight/obese}$=3.607 vs. $M_{25°C,6500K,overweight/obese}$=3.625). However, during exposure to the cool temperature, higher thermal comfort rates were more likely to be associated with higher lighting CCT compared to lower lighting CCT ($M_{20°C,6500K,overweight/obese}$=3.750 vs. $M_{20°C,2700K,overweight/obese}$=3.042). In contrast, higher lighting CCT had the opposite effect on participants with healthy BMI. In fact, participants with healthy BMI were more likely to have higher thermal comfort rates in the warm temperature when they were exposed to higher lighting CCT ($M_{25°C,6500K,healthy}$=4.046 vs. $M_{25°C,2700K,healthy}$=3.816), while in cool temperature, lower CCT values resulted in higher comfort rates on average ($M_{20°C,2700K,healthy}$=2.938 vs. $M_{20°C,6500K,healthy}$=2.744). Although anecdotal evidence suggests that lighting CCT can affect thermal comfort, the significance of the temperature × lighting CCT interaction was not proved in our study, probably because the designed conditions were not too far from comfort ranges [96]. Accordingly, Luo et al. argued that a large inter-individual variation exists in the color-temperature association, and the temperature × lighting CCT interaction depends on exposure time as well, which can contradict previous findings [96]. Additionally, while thermal perception was reported to be more sensitive to CCT changes in warm environments [97], our results controvert this prior finding, at least for overweight/obese participants. While previous IEQ interaction studies have not included BMI in thermal comfort analysis, and even though no main effect of BMI on thermal comfort was found, the BMI status of participants affected the interaction effect between lighting CCT and temperature. While in a cool environment, healthy participants were less comfortable with 6500 K lighting, under the same lighting condition, the thermal comfort of overweight participants was much higher, which is aligned with most BMI-thermal studies [98]. With respect to gender, females were reported to be more susceptible to temperature fluctuations and are generally more dissatisfied than males in relation to the thermal environment [36]. This is in line with our findings, where women felt less comfortable with the thermal environment on average (M_{female}=3.365 vs. M_{male}=3.450); however, our findings did not confirm the significance of this gender-based variation.

Visual Comfort

Lighting CCT had a marginally significant effect on visual comfort assessed by comfort votes regarding lighting color ($F_{1,50} = 3.731,\ p = 0.059,\ \eta_p^2 = 0.069$) (**Table 4**). On average, participants were more comfortable with 2700 K lighting (M_{2700K}=3.589) compared to 6500 K lighting (M_{6500K}=3.267). This is in contrast with previous research where visual comfort did not significantly differ between 2700 K and 5700 K CCTs [31]. While the significance of temperature's interaction with lighting CCT's effect on visual comfort was not identified, some earlier studies found this kind of effect [22], [33]. For instance, at 19 °C, daylight tinted by the blue glazing was evaluated as less comfortable than by the orange glazing [99]. Additionally, it was noted that gender moderated the effect of lighting on visual comfort ($F_{1,48} = 9.142,\ p = 0.004,\ \eta_p^2 = 0.160$) (**Table 4**) such that variations in lighting color was more likely to affect females' visual comfort ($M_{2700K,female}$=3.764 vs. $M_{6500K,female}$=2.971) than male's ($M_{2700K,male}$=3.413 vs. $M_{6500K,male}$=3.563) (**Figure 7**). However, no earlier evidence was found in support of this interaction effect.

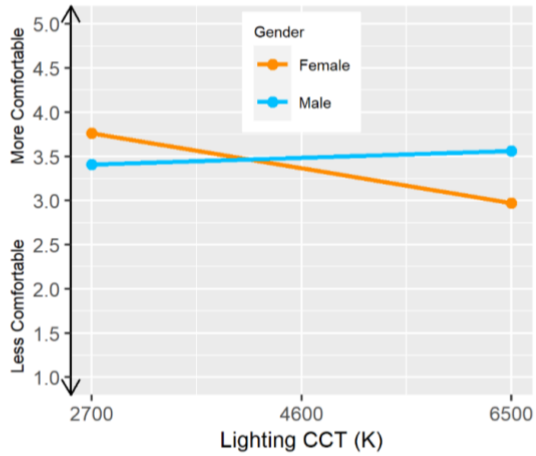


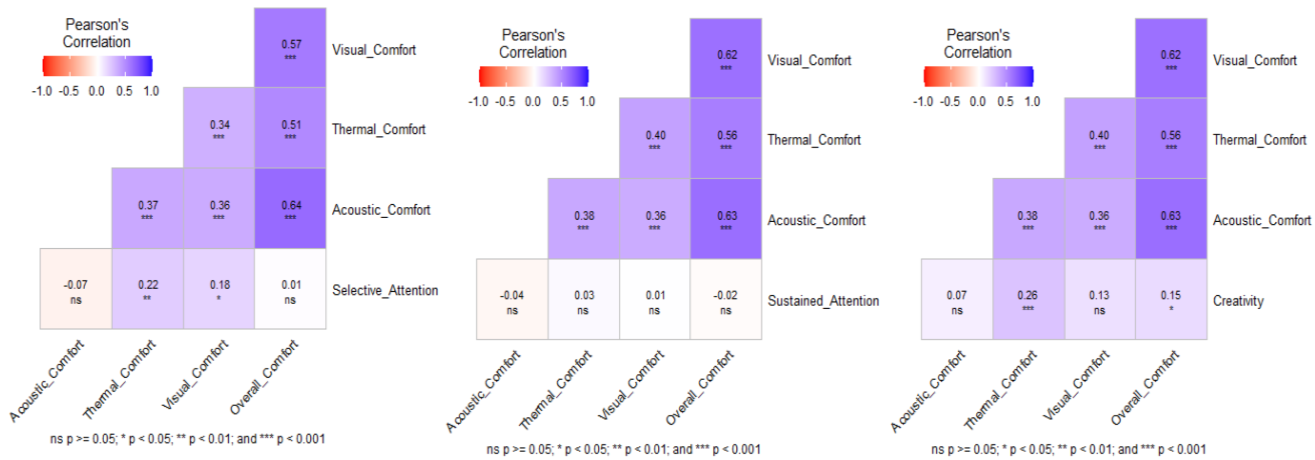
Figure 6. Interaction effects of IEQ factors on visual comfort

Overall comfort

Noise had a main effect on overall comfort votes ($F_{1,50} = 10.486$, $p = 0.002$, $\eta_p^2 = 0.173$) (**Table 4**), such that participants were more comfortable with the low noise level (M_{50dB}=3.668) compared to the high noise level (M_{65dB}=3.356). Additionally, the temperature had a marginally significant effect on overall comfort ($F_{1,50} = 3.576$, $p = 0.064$, $\eta_p^2 = 0.067$) (**Table 4**) in a way that participants found 25°C more comfortable ($M_{25°C}$=3.784) than 20 °C ($M_{20°C}$=3.240). The influential effects of noise level and temperature on overall perceived comfort were reported in previous studies [34]. The significance of lighting CCT effect on overall IEQ comfort was not identified, which is in line with earlier studies where no significant relationship between CCTs and overall comfort was found [64].

Correlation between cognitive performance and perceived comfort

As presented in **Figure 8**, it can be inferred that cognitive performance indicators are positively correlated with perceived comfort votes. As depicted in **Figure 8a**, selective attention is significantly correlated with thermal comfort (r=0.22, N=192, *p*=0.003) and visual comfort (r=0.18, N=192, p=0.011), and thus, selective attention improved while participants were more comfortable with their thermal and visual environment. The correlation of selective attention with acoustic comfort and overall comfort is extremely low and can be considered as having no correlation. Sustained attention had no correlation with perceived comfort votes, as illustrated in **Figure 8b**. Additionally, thermal comfort has a significant correlation (r=0.26, N=208, $p < 0.001$) with creativity, such that participants' creativity scores were higher when they felt more thermally comfortable (**Figure 8c**). While the correlation of acoustic comfort and visual comfort with creativity was slightly correlated, overall comfort was significantly correlated with creativity (r=0.15, N=208, *p*=0.026), which was likely driven by the thermal environment.



(a) (b) (c)

Figure 7. Correlations between cognitive performance indicators and perceived IEQ comfort: **(a)** selective attention, **(b)** sustained attention, **(c)** creativity

In relation to cognitive functioning, it is noteworthy that selective attention and creativity demonstrated the strongest correlation with thermal comfort among the various domains of comfort examined in this study, followed closely by visual comfort. Studying brain activity can shed light on these results, as previous research demonstrated that the relative power of electroencephalogram (EEG) signals have a significant correlation with thermal comfort and with the performance of neurobehavioral tests [100]. Likewise, suggestions have been provided for improving cognitive functioning through the improvement of IEQ comfort [101]. Our findings are compatible with other studies that indicated correlations between subjective IEQ comfort votes and perceived functioning [102]. However, observing no significant correlations between acoustic comfort and cognitive functions was unexpected, given that overall comfort was significantly affected by the acoustic conditions. Overall, cognitive functioning can be correlated with IEQ comfort, and thus further consideration should be given to improve IEQ comfort where enhancement in cognitive functioning is crucial.

CONCLUSIONS

Improvements in IEQ in the work/study spaces are likely to yield continuing benefits to young adults' cognitive performance and comfort. A mixed-design experimental study was employed to understand the interaction effects between temperature, lighting color, and noise on selective attention, sustained attention, creativity, acoustic comfort, thermal comfort, visual comfort, and overall IEQ comfort of young adults in open plan offices in the North American Mediterranean climate. The explored environmental conditions included 20 °C and 25 °C as representatives of cool and warm temperatures, 2700 K and 6500 K as representatives of warm and cool lighting colors, as well as 50 dB and 65 dB crowd-talking noises as low and high noise levels. Through the integration of gender and BMI, the effect of individual differences was investigated as well. The results showed that temperature interacted with the noise level and lighting CCT's main effects on selective attention. In regard to sustained attention, no significant main or interaction effect of IEQ factors was noted. Creativity was influenced by gender and its interaction with noise level as well as the interaction between noise level and lighting CCT. Temperature's main effect and its interaction with noise level on acoustic comfort were found to be significant. Additionally, the temperature, in conjunction with lighting CCT and BMI, affected thermal comfort. Moreover, the interaction between gender and lighting was found influential on visual comfort. Finally, noise level and temperature affected the overall comfort. The correlations between objective performance indicators and subjective comfort votes reflected the importance of IEQ comfort in cognitive functioning.

The study findings can have implications for building designers, researchers, facility managers, as well as the developers of IEQ monitoring and control systems. To boost selective attention capabilities in cool thermal settings, a higher noise level and a cooler lighting color are preferable. However, in warm thermal settings, a lower noise level and a warmer lighting color can improve selective attention capabilities. The creativity abilities of female office workers in cool and warm thermal settings can be enhanced by utilizing higher and lower noise levels, respectively, while the creativity of male office workers can be improved with lower and higher noise levels in cool and warm thermal settings. To improve acoustic comfort while setting the temperature to a warmer setpoint, the utilization of a lower noise level is more desirable. Additionally, when the noise level is lower in indoor environments, cool lighting color can enhance the perceived acoustic comfort. Achieving optimal thermal comfort requires personalized approaches that take into account individual physiological differences. For participants with healthy BMI, warm lighting color can improve perceived thermal comfort in warm thermal settings, while cool lighting color is preferable in cool thermal settings. On the other hand, cool lighting color is more desirable for participants with overweight/obesity BMI status while working in cool thermal settings. To improve visual comfort, cool and warm lighting colors are preferable for male and female office workers, respectively. Overall perceived comfort can be boosted with lower noise levels and warmer thermal settings. In summary, specific combinations of noise level and lighting color were identified to optimize selective attention, creativity, acoustic comfort, thermal comfort, visual comfort, and overall perceived comfort in different thermal settings. The findings underscore the importance of tailoring environmental factors to individual differences to enhance cognitive performance and perceived comfort in office settings. It should be noted that the variations in individual differences, IEQ factors, and cognitive task types necessitate more human-centered approaches that can address personalized IEQ preferences across different times, locations, and cognitive tasks.

According to the literature, most people can maintain high performance for a short time under unpleasant environmental conditions when trying to do their best [87], and a significant change in performance may be identified if the investigated range of environmental stressors spans beyond near-optimum ranges [18]. However, in our study, the explored conditions affected the cognitive performance through their interactions rather than their individual main effects. While anecdotally we know that study participants have stayed in the Northern American Mediterranean climate somewhere between 4 months to 2 years, we have not collected the data about duration of residency. Future studies should consider this parameter to ensued that the participants fully climatized to the local climate. Additionally, the absence of main effects of IEQ factors on cognitive performance metrics could be related to the counteracting effects of the individual IEQ factors on each other. Coping mechanisms of occupants' psychophysiological systems and adaptive capability would be another reason for these results. For instance, Razmjou argued that in low-demand tasks, a deficit of mental performance in high temperatures could be offset by heat-related stimulated arousal [103], [104]. However, exposure duration, the existence of other IEQ factors, as well as task type and worker demographics might affect the studied outcomes; therefore, future studies should explore these variables more in-depth. Moreover, while gender and body mass index (BMI) were accounted for in our analysis, it is important to recognize that a multitude of other factors, including age and ethnicity, may also exert an influence on the response to environmental stressors [5]. Future studies should seek to clarify the precise nature and underlying mechanism behind observed effects. Cognitive functioning and human psychophysiology are still untapped research venues in the IEQ realm that could lead to new breakthroughs in multi-domain studies integrating architectural design, civil engineering, building science, public health, and psychology. Therefore, given that many of our findings are novel, they need to be replicated in further studies.

ACKNOWLEDGMENTS

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