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Subjective Impression of an Office with Biophilic Design and Blue Lighting: A Pilot Study

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Abstract: This paper investigates and compares people's subjective impression of an office with a biophilic design and blue lighting. Existing studies have examined their influence on perception separately, but how they compare is unclear. Additionally, only a few studies have used an office setting as a case study. To address this research gap, this study collected people's ratings and rankings of four simulated interior scenes of a private office using an online survey. The scenes include blue lighting, a biophilic design with daylight and view, a biophilic design with indoor plants, and a non-biophilic baseline with conventional white lighting. A total of 284 complete responses were collected and analyzed using a mixed-effect model. It was found that the two biophilic designs improved people's perception of the office compared to the base case. The biophilic design with access to daylight and view outperformed the space with indoor plants in all the examined perceptual categories, specifically how the office space was perceived by participants as brighter, more comfortable, and spacious. On the contrary, the space with blue lighting decreased people's ratings in most perceptual attributes in comparison to the baseline. The negative influence was notably significant in how lively, comfortable, bright, and appealing the space was perceived as being by participants. Subjects' preference rankings of the four simulated office spaces showed a similar pattern.

Keywords: human perception; biophilic design; blue light; computer rendering

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1. Introduction

People in modern societies spend more than 90% of their time indoors [1]. Indoor environmental quality (IEQ) plays an important role in occupants' health, well-being, and productivity [2]. In a recent study [3], IEQ has been classified into tangible factors (indoor air quality, lighting, noise, and temperature) and intangible factors (biophilia and views, cleanliness and maintenance, furnishing, layout, and personal control). Biophilic design, originating from the concept of biophilia, hypothesizes that humans have an innate connection with nature [4]. This notion has been promoted as a promising strategy to incorporate the positive experiences of nature into the design of a built environment [5]. A large body of studies has been conducted to examine the benefits of bringing nature indoors, many of which focus on access to daylight (with or without view) and indoor plants. Daylight through windows has an essential impact on human health and well-being as it regulates their biological clock and influences their psychological states. Several review studies have summarized the benefits of daylight ingress in a built environment [6–10]. For instance, access to daylight and/or view was found to reduce patients' length of stay [11–13], help with stress reduction and recovery [14,15], improve cognitive performance [16,17], as well as increase office workers' job satisfaction [18]. Similarly, growing indoor plants is another common biophilic strategy to bring nature indoors. Bringslimark et al. [19] conducted a relevant review of experimental studies and found that indoor plants can provide psychological benefits, such as reduced stress and increased pain tolerance, but in general, the results seem to be mixed. A more recent study by Han and Ruan [20] reviewed the effects of indoor plants on self-reported perceptions, suggesting that rooms with plants are perceived more positively. Specifically, indoor plants can increase positive emotions (friendliness, kindness, happiness, cheerfulness, calmness, peacefulness, pleasantness, relaxation, and warmth), reduce negative psychological perceptions (stress and anxiety), and relieve physical discomfort. Aydogan and Cerone [21] summarized the physiological benefits of plants, including reduced illness and stress, decreased sick leave, and lowered mortality. In terms of cognitive performance, indoor plants are associated with reduced attention-deficit/hyperactivity disorder symptoms, reduced mental fatigue, and improved productivity and/or attitude.

As a tangible IEQ factor, lighting also influences occupants' health and well-being [22,23]. Light is electromagnetic radiation that can be perceived by human eyes. The color of visible light depends on its wavelength, which is between 380 nm and 760 nm [24]. Red has the longest wavelength and violet has the shortest wavelength. Blue light has a wavelength that ranges from approximately 380 nm and 500 nm, making it one of the highest-energy wavelengths. In the lighting industry, Correlated Color Temperature (CCT), measured in degrees of Kelvin (K), is used to describe the color appearance of a light source. Warm light sources with a low CCT (2000 K–3000 K), such as incandescent bulbs, result in more light in the red, orange, and yellow range. Cool light sources with a high color temperature (>4000 K), such as fluorescent lamps, feature more bluish light. Within an indoor space, the light intensity is measured by illuminance, which quantifies the amount of light falling on a surface, in a unit of footcandles or lux.

The advancement in lighting technology has increased people's interest in the use of colored lighting, especially blue lighting in interior spaces [25–28]. For example, colored lighting can be used to create a pleasant ambiance. In general, light and color are reported to have both physiological and psychological effects on people. From a biological perspective, melatonin is especially suppressed by short-wavelength (blue-shifted) light, influencing the circadian rhythm [29–31]. Disruptions to the circadian rhythm can further cause mood disorders [32,33]. Earlier studies also indicate the superiority of short-wavelength light on alertness augmentation and/or sleepiness reduction due to melatonin suppression [26,34–36]. For instance, Viola et al. [26] investigated how blue-enriched white light in the workplace improved alertness, performance, and sleep quality. In their study, 104 white-collar workers were exposed to two lighting conditions: one with blue-enriched lighting and the other with white lighting, each for four weeks. They discovered that the blue-enriched lighting improved self-reported alertness, mood, performance, and sleep quality. Similarly, the study by Keis et al. [25] suggested that blue-enriched white lighting in a classroom improved students' cognitive performance in comparison to a standard lighting condition. Moreover, recent studies have reported that colored light has an impact on alertness without necessarily stimulating the melatonin pathway [37–39]. Meanwhile, colored lighting changes the appearance of the interior and could further impact people's emotions, cognitive performance, and perception of the interior space.

As discussed above, both biophilic design (indoor plants and daylight access) and blue lighting could exert positive impacts on people's emotions, mood, cognitive performance, and perception of the interior space, which could further support their health and well-being. Despite the similar effects they share, they are two distinguished indoor environmental design and intervention strategies. When designing or retrofitting an existing space, it is beneficial to know what strategy could further improve the indoor environment. To the best of our knowledge, no research has been conducted to compare these two indoor design interventions. This study is an exploration to address this research gap. Specifically, we investigated people's subjective impressions of an office with the two interior design strategies. In particular, two out of the fourteen Patterns of Biophilic Design, namely, "visual connection with nature" and "dynamic and diffuse light" [40], were studied. These two patterns were represented by indoor plants and daylight and access to outdoor views. These two patterns were selected based on several considerations: (1) they are the most common biophilic design strategies in indoor spaces; (2) previous studies have provided direct evidence on how they influence people's impressions [14,15,41,42], and (3) they could be easily created and rendered with most software.

In this study, computer renderings were used to generate "realistic" interior scenes of a private office. Computer-generated images have been widely used in previous studies to collect people's subjective evaluation of interior scenes [15,16,43–49]. This method has been verified for its accuracy in representing actual scenes, especially for lighting quality evaluation [46,50–55]. It should be noted that this paper only focused on the psychological influence of the interior scenes. The physiological influence will be examined in future studies where participants can be immersed in physical indoor environments.

The effects of color and lighting have been studied by different researchers and documented in a large body of research. However, the results are not consistent. Based on the research objectives of this paper, studies on the influence of interior color and colored lighting on people's perception, emotion, and/or cognitive performance were selected and reviewed. The non-visual effects of colored lighting have been widely investigated and reported in various studies. These studies are excluded from the literature review in this paper as the non-visual effects are not relevant to this experimental study.

1.1. Influence of Interior Color on Impression, Emotion, and/or Cognitive Performance

Many studies have examined the effects of interior color on people; a few are summarized in this paper. In an early study by Acking and Küller [56], 89 colored varieties of the same room were presented to the subjects. The rooms with interior walls of higher chromaticity were perceived with more complexity and lower unity (coherence). In a cross-cultural study, Küller et al. [57] discovered that people who had the most colorful work environment reported higher emotional status throughout the year. Yildirim et al. [43,58,59] conducted a series of studies on the effects of interior color on mood, perception, preference, and cognitive performance. More specifically, they carried out a two-stage study in a restaurant, in which the interior color was changed from yellow to violet [58]. Participants' evaluations using bipolar scales indicated that customers perceived the violet interior more positively in all the examined atmospheric attributes (e.g., "attractive/unattractive"). Later, they examined the effects of interior color on mood and preferences using digital images of two living rooms [43]. The red room was reported to be associated with higher arousal, evoking more exciting and stimulating emotions compared to a blue or achromatic-colored room. On the other hand, the blue room evoked more feelings of spaciousness, restfulness, calm, and peacefulness than the red room. Recently, Yildirim et al. [59] investigated people's perception of three classrooms with different colored interiors: cream (neutral color), blue (cool color), and pink (warm color). The results showed the blue room was perceived as more pleasant, happier, comfortable, roomy, peaceful, and calm, while less attractive, exciting, and dynamic. These findings are in accord with the results from their previous studies and other relevant studies [43,58,60,61]. These studies indicate that an interior with cool colors such as blue could evoke a pleasant, peaceful, calm, and comfortable perception, while warm colors such as red could make a room appear more stimulating, but less spacious.

Nevertheless, several studies reported no effects of interior color on measures of emotion and cognitive performance. Kwallek et al. [62] examined the effects of nine monochromatic colors on clerical tasks and workers' moods and did not observe any overall major effect of office interior color on mood. Interestingly, participants reported the white office as the least distracting and most preferable, while they made more proofreading errors than in the blue or red office. This finding is consistent with their previous study in which a white office was rated the most spacious and pleasant, compared to a blue-green office or a red one [63]. The authors assumed that the discrepancy between the experimental result and subjective evaluation was due to social expectations, governing that white is the most "appropriate" color for an office interior. Castell et al. [64] investigated the effects of interior color on cognitive performance and emotion. They compared three commercially available interior colors that were advertised to have specific effects on cognitive performance and emotional state with a neutral white. In their experiment, 170 students were randomly assigned to be exposed to interior walls that were painted in one of the four colors and performed five cognitive tasks. Their self-reported emotional state before and after the cognitive tasks was collected using the SAM (self-assessment manikin) scales [65]. It was found that the interior color did not have the anticipated effects, either on cognitive performance or on the emotion of the subjects. As summarized above, the effects of interior color on impression, emotional state, and cognitive performance are not conclusive and further research is required.

1.2. Influence of Lighting Color on Impression, Emotion, and Behavior

In the literature, there have been several studies investigating the effects of colored lighting on people's impressions, emotional states, and behavior. In the study by Minguillon et al. [66], twelve participants were stressed and then exposed to two lighting conditions within a chromotherapy room. Collected biological measures, such as electroencephalographic (ECG), revealed that blue light accelerated post-stress relaxation compared to conventional white light. The authors suggested the use of blue light in clinical and educational environments (i.e., the time-out room in high schools). Kuijsters et al. [28] used colored lighting to create ambiances with a recognizable, positive affective meaning in an experimental room. Later, they investigated whether ambiance could be used to mitigate negative moods in the elderly [27]. Specifically, two positive ambiances, including an activating ambiance using cool color (colors that appear blue) lighting and a cozy ambiance using warm color (colors that appear orange), as well as a neutral ambiance using conventional white lighting were created. Participants were immersed in one of these rooms after a sad mood or anxiety was induced. Both self-reported mood measurements and physiological measures (skin conductance response and ECG) indicated that, compared to the neutral ambiance, the activating ambiance was more helpful in recovery from the sad mood and the cozy ambiance was more effective in calming the anxious participants.

In more recent studies, the effects of more lighting colors were directly investigated in laboratory settings. In particular, Wu and Wang [67] examined the effects of Light-Emitting Diode (LED) color temperature and illuminance on customers' emotions and impressions of a restaurant. It appeared that customers were more likely to enjoy an atmosphere created by warm lighting than cool lighting, where they felt happy, joyful, pleasant, relaxed, and private. Additionally, higher illuminance seemed to evoke higher sensations of pleasure, arousal, dominance, and spaciousness. Likewise, in his Ph.D. dissertation, Lee [68] investigated how LED lighting color influenced human emotional states, behavioral intentions, and spatial impressions. Of the six lighting colors, blue and red were found to show dominant contrasting results to the other colors. More specifically, blue lighting showed the highest scores for pleasure, significantly higher than the lighting of warm colors (i.e., red and orange). Red lighting had the highest ratings on arousal, which was significantly higher than the lighting of cool colors (i.e., blue and green). They also discovered that people might want (or try) to avoid or leave a room with red lighting while they might want (or try) to approach or stay longer in a room with blue lighting. In terms of spatial impression, blue lighting had the highest ratings for attractiveness, comfort, pleasantness, and relaxation, whereas red lighting had the lowest ratings for these impressions. Yellow lighting was perceived as the most cheerful of the six lighting alternatives.

Daylight through the glazing with saturated colors can also influence people's perception of the interior environment. In a recent study, Chinazzo et al. [69] investigated the effect of indoor temperature and glazing with saturated color on people's visual perception of daylight. Three colors were selected and compared, including orange, neutral, and blue. A total of 75 participants experienced all three colored glazing alternatives in a randomized order. Their visual perception evaluations were collected using a questionnaire, including the color of light evaluation and visual environment evaluation. The result indicated that the neutral glazing was assessed as the most comfortable, acceptable, and pleasant, compared to the orange and blue colored glazing in terms of the color of the light. The glazing of neutral color was also the most selected first choice when subjects were asked to rank the three alternatives. There was no difference between the responses to the blue and orange glazing in terms of color comfort, acceptability, and pleasantness when the whole sample was analyzed. For the evaluation of the visual environment, the neutral glazing was also rated the best regarding brightness comfort, overall visual environment comfort, lighting comfort, and lighting pleasantness. The orange glazing had the lowest rating on brightness sensation. This was probably because the illuminance under this condition was the lowest. However, it had a higher rating on brightness comfort compared to the neutral glazing. Meanwhile, it was reported to be associated with the most relaxing daylight. The researchers also stated that indoor temperature had cross-modal effects on the visual perception of both the color of light and the visual environment. To summarize, more studies, especially experimental ones, are required to examine the influence of colored lighting to derive more consistent conclusions.

2. Materials and Methods

2.1. Participants

The presented study was approved by the Carnegie Mellon University Institutional Review Board. It was an online survey that was completely voluntary and no financial compensation was provided. No personal data were collected except for gender, age, years of education in architectural and interior lighting, and years of working experience in a professional architectural setting. Participants were recruited through electronic mailing lists of students, faculty, and staff from the School of Architecture at Carnegie Mellon University, as well as the Society of Building Science Educators (SBSE) mailing list. The survey link was also posted on several social media sites, including WeChat, Facebook, Instagram, and LinkedIn. Digital informed consent from all participants was obtained before they could start the survey. Subjects agreed to participate after being informed about the background and purpose of the study and their freedom to quit the survey at any time. Starting the survey was considered to indicate participant consent and they were adults over the age of 18. The use of digital consent was approved by the Institutional Review Board. The survey was conducted in April 2020. In total, 295 participants took the survey and 284 of the responses were complete.

2.2. Environmental Stimuli

The scenes used as environmental stimuli in this study correspond to four variations of a private office. The office geometry was created in Rhinoceros (Rhino, version 6.0), a commercial 3D computer graphics and computer-aided design application software. Four interior scenes of the office were then made using Enscape (Enscape, version 2.7), a commercial real-time rendering and virtual reality plugin in Rhino. As shown in Figure 1, the baseline office (a) was devoid of a biophilic design with typical white lighting. The second office (b) was a non-biophilic design with blue lighting. The number, color, and brightness of the blue lights were set according to the lights used in a field study [27], to represent a more realistic lighting condition in real-life settings. The other two offices ((c) and (d)) were created with indoor plants and daylight with a view to the outside, respectively. The lighting settings for the baseline and the office with plants were the same.

Figure 1. The four rendered scenes of an office with different design interventions.

2.3. *Online Survey and Questionnaire Design*

The online tool Qualtrics (Qualtrics, Provo, UT, USA) was used to create and distribute the survey. The four selected scenes were incorporated into the online survey and shown to the participants in random order. Their opinions of each scene were collected using semantic differential scaling. The survey was developed based on previous relevant studies on lighting, daylighting, and indoor greenery [18,27,46,67], with some of the questions modified for this study. The questionnaire consisted of two sections. In the first section, participants were asked about demographic information including their gender, age, educational background, and work experience in architectural settings. The second section measured participants' impressions of the rendered scenes, using a seven-point semantic differential scale ranging from 1 (most negative) to 7 (most positive). The seven-point scale was selected based on previous research findings indicating that more alternative options for answers show a significant increase in reliability and validity up to seven points. This means that more points within the scale do not lead to a significant quality improvement in the measurement [70]. in addition, unipolar semantics was applied to avoid bias that might be introduced by bipolar semantics. For instance, a bipolar rating scale from calming to exciting does not offer a negative evaluation, so it does not allow for the identification of conditions that might range from exciting to disturbing, or from calming to dull [18]. Such a rating scale presumes that the stimulus cannot be both calming and exciting, or neither calming nor exciting. The semantic words were collected from the literature and selected for the office space in this study, including lively, calming, comfortable, interesting, spacious, bright, cheerful, and appealing. The study variables are listed in Table 1. Participants were also asked to rank the four scenes from 1 (the most preferred) to 4 (the least preferred) based on their preferences. At the end of the questionnaire, two open questions were asked to understand what factors might influence participants' ratings.

Table 1. Overview of the independent variable and dependent variables.

Independent Variable (IV)	Dependent Variables (DV)
IV1. Interior design variations (4 different scenes, (a)–(d) in Figure 1)	DV1. Lively DV2. Calming DV3. Comfortable DV4. Interesting DV5. Spacious DV6. Appealing DV7. Cheerful DV8. Bright

2.4. Data Analysis

To account for the rating variation between different participants on the same design, a linear mixed-effect model was applied. Linear mixed-effect models are an extension of simple linear models that allow for both fixed and random effects. In this study, fixed effects are the variation that is explained by the independent variables of interest, i.e., different design iterations. In contrast, random effects are the variations that are not explained by the independent variables of interest, i.e., variations in the ratings of the same design by different participants. Particularly, the participants were treated as a random intercept to control the variability across individuals. The baseline was used as the reference group and each of the other three interior interventions was examined in the model to obtain the beta estimate and 95% confidence interval for each semantic rating. A two-sided alpha level of 0.05 was used to determine statistical significance. For emotional state or space impression rating:

$$Y_{i,j} = \beta_0 + \beta_1 \text{blueLight} + \beta_2 \text{plant} + \beta_3 \text{daylight} + u_j + e_{i,j} \tag{1}$$

$$e_{i,j} \sim N\left(u_e,\ \sigma_e^2\right) \tag{2}$$

$$u_j \sim N\left(u_\beta,\ \sigma_\beta^2\right) \tag{3}$$

where, $Y_{i,j}$ = the perception rating i by participant j; blueLight = 1 if the image displayed to the participant represented the interior design with blue lighting otherwise 0; plant = 1 if the image displayed to the participant represented the interior design with indoor plants otherwise 0; daylight = 1 if the image displayed to the participant represented the interior design with daylight and view otherwise 0; β_1 = fixed effect of blue lighting compared to the baseline design; β_2 = fixed effect of indoor plants compared to the baseline design; β_3 = fixed effect of daylight and view compared to the baseline design; μ_j = random effect for participant j, which follows a normal distribution with a mean of μ_β and a variance of ${\sigma^2}_\beta$; $e_{i,j}$ = residual of perception rating i by participant j, which follows a normal distribution with a mean of μ_e and a variance of ${\sigma^2}_e$. Analyses were performed using the open-source statistical package R (v.3.5.6) with the package "arm" (v.1.10.1).

3. Results

This section is divided into subheadings. It provides a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.1. Demographics

In total, complete responses were collected from 284 participants after excluding 11 incomplete ones. Table 2 shows the characteristics of the study population. In general, there were slightly more female subjects (56.7%) than male subjects (43.0%), and most of them (68.3%) were aged between 21 to 30 years. Concerning educational background, 21.1% of the respondents reported having more than six years of formal architecture, landscape architecture, urban design/planning, lighting design, or interior design education; 21.8% between 1 to 5 years; and 57.0% had no relevant education background at all. Regarding work experience, most of the subjects (67.3%) had no work experience in a professional architectural setting.

Table 2. Characteristics of the study population.

Variable	Number (Percentage)
Gender	
Male	122 (43.0%)
Female	161 (56.7%)
Prefer not to answer	1 (0.4%)
Age	
<=20	4 (1.4%)
21–30	194 (68.3%)
31–40	46 (16.2%)
>40	40 (14.1%)
Educational background (years of formal education in architecture, landscape architecture, urban design/planning, interior design, or lighting design)	
0 years	162 (57.0%)
1–5 years	62 (21.8%)
>=6 years	60 (21.1%)
Work experience (years of working experience in a professional architectural setting)	
0 years	191 (67.3%)
1–3 years	47 (16.5%)

3.2. Space Perception

Table 3 and Figure 2 show the results from the mixed-effect model analysis. Overall, the examined three interior designs had a significant impact on people's impression of the interior scene compared to the baseline design. Particularly, the two biophilic designs increased participants' ratings, while the blue lighting design decreased their ratings. Furthermore, the two biophilic designs had the most positive effect on how lively, cheerful, interesting, appealing, and bright the office was perceived to be, while the design with blue lighting reduced the ratings of lively, cheerful, appealing, bright, and comfortable.

Table 3. Results from the mixed-effect model analysis.

Dependent Variable	Pairwise Comparison	Mean Difference	Std. Error	*t* Value	*p*-Value
Lively	Blue lighting-Baseline	−0.80	0.10	−7.95	$p < 0.001$ *
	Plant-Baseline	1.19	0.10	11.97	$p < 0.001$ *
	Daylight and view- Baseline	1.53	0.10	15.29	$p < 0.001$ *
Calming	Blue lighting-Baseline	−0.11	0.11	−1.04	0.298
	Plant-Baseline	0.29	0.11	2.63	0.008 *
	Daylight and view- Baseline	0.57	0.11	5.24	$p < 0.001$ *
Comfortable	Blue lighting-Baseline	−0.65	0.10	−6.66	$p < 0.001$ *
	Plant-Baseline	0.43	0.10	4.48	$p < 0.001$ *
	Daylight and view- Baseline	1.15	0.10	11.83	$p < 0.001$ *
Interesting	Blue lighting-Baseline	−0.28	0.10	−2.80	0.005 *
	Plant-Baseline	1.08	0.10	10.74	$p < 0.001$ *
	Daylight and view- Baseline	1.61	0.10	15.96	$p < 0.001$ *
Spacious	Blue lighting-Baseline	−0.42	0.09	−4.68	$p < 0.001$ *
	Plant-Baseline	0.08	0.09	0.90	0.366
	Daylight and view- Baseline	1.04	0.09	11.55	$p < 0.001$ *
Cheerful	Blue lighting-Baseline	−0.73	0.10	−7.51	0.005 *
	Plant-Baseline	0.98	0.10	10.07	$p < 0.001$ *
	Daylight and view- Baseline	1.65	0.10	16.99	$p < 0.001$ *
Appealing	Blue lighting-Baseline	−0.66	0.10	−6.55	$p < 0.001$ *
	Plant-Baseline	0.74	0.10	7.36	$p < 0.001$ *
	Daylight and view- Baseline	1.43	0.10	14.15	$p < 0.001$ *
Bright	Blue lighting-Baseline	−1.26	0.11	−11.82	$p < 0.001$ *
	Plant-Baseline	0.54	0.11	5.11	$p < 0.001$ *
	Daylight and view- Baseline	1.86	0.11	17.43	$p < 0.001$ *
	Daylight and view- Baseline	1.04	0.09	11.55	$p < 0.001$ *

* $p < 0.05$.

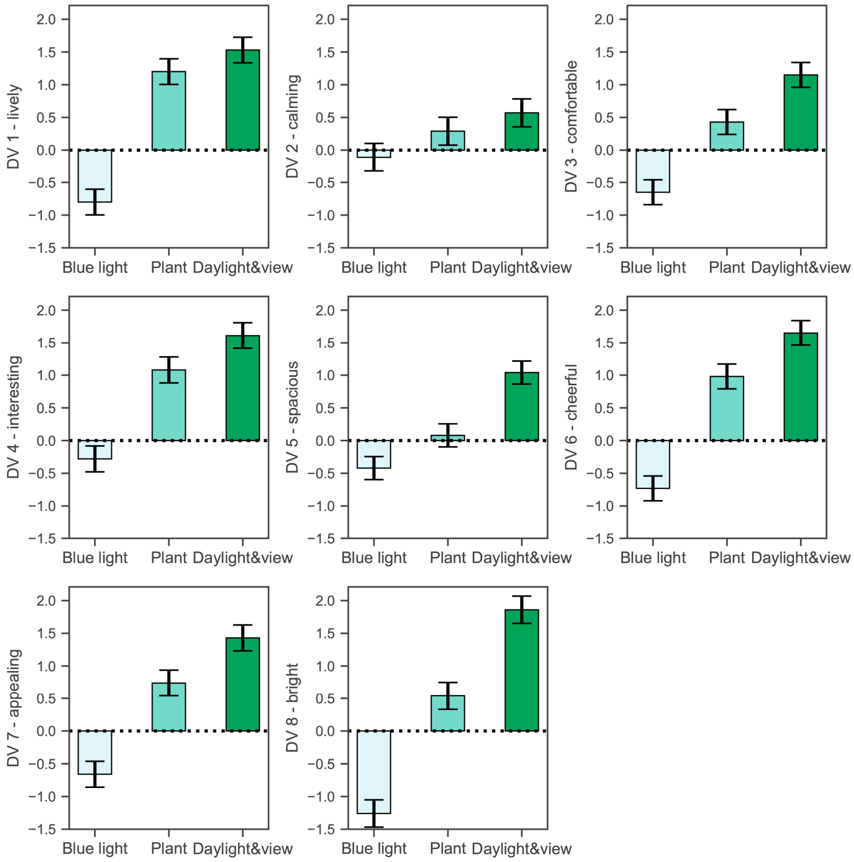

Figure 2. Estimated effects (with 95% CI) of the three design iterations compared to the baseline.

Of the two biophilic designs, the one with daylight and view has a greater impact on participants' perception of the space than the one with indoor plants. Figure 2 visualizes the estimated fixed effects (β and 95% confidence interval) of the three designs, relative to the baseline on different semantic ratings. Specifically, the design with daylight and view was found to have a statistically significant association with the brightness rating (1.86, 95% CI: 1.65, 2.06), followed by a positive effect on the cheerfulness rating (1.65, 95% CI: 1.46, 1.84), and an increase in the rating of interesting (1.61, 95% CI: 1.41, 1.81), lively (1.53, 95% CI: 1.33, 1.73), and appealing (1.43, 95% CI: 1.23, 1.63). It was also related to a smaller increase in comfort rating (1.15, 95% CI: 0.96, 1.34) and spaciousness rating (1.04, 95% CI: 0.86, 1.22), as well as the smallest increase in how calming the space was perceived as being (0.57, 95% CI: 0.36, 0.78).

For the design with indoor plants, statistically significant effects were found between the ratings of lively (1.20, 95% CI: 1.00, 1.39), followed by interesting (1.08, 95% CI: 0.89, 1.28), cheerful (0.98, 95% CI: 0.79, 1.17), and appealing (0.74, 95% CI: 0.54, 0.94). The influence on the rating of bright (0.54, 95% CI: 0.79, 1.17), comfortable (0.43, 95% CI: 0.24, 0.62), and calming (0.29, 95% CI: 0.07, 0.50) was relatively smaller. Table 3 indicates that this design did not significantly impact how spacious the office was perceived as being by the participants. As shown in Figure 2, the effect associated with this design was consistently smaller than the design with daylight and view, regarding all the other seven semantic categories.

In contrast, the design with blue lighting had a consistently negative impact on people's ratings, especially concerning brightness rating (−1.26, 95% CI: −1.47, −1.05). It was also associated with a considerable reduction in ratings of lively (−0.80, 95% CI: −0.99, −0.60), cheerful (−0.73, 95% CI: −0.92, −0.54), appealing (−0.66, 95% CI: −0.86, −0.46), and comfortable (−0.65, 95% CI: −0.86, −0.46). The smallest effect for this design was observed regarding how interesting the office was perceived by the participants (−0.28, 95% CI: −0.48, −0.08), and no statistically significant effect was found on how calming the office was perceived as being.

3.3. Preference Ranking

Figure 3 shows the ranking distribution for each interior design. As shown in the figure, 78.5% of the participants ranked the biophilic design with daylight and view as the most preferred design option. About two-thirds of the participants ranked the biophilic design with indoor plants the second (57.7%), and the baseline the third (60.6%). Additionally, 77.5% of the respondents rated the office with blue lighting as the least preferred design. In general, the ranking was consistent with the perception rating. The ranking order by each participant was also examined. It was found that 50.5% of the participants had the same ranking order: daylight and view (1st)—indoor plants (2nd)—baseline (3rd)—blue light (4th), which aligns with the previous analysis. The second most common ranking order was daylight and view (1st)—baseline (2nd)—indoor plants (3rd)—blue light (4th), which accounts for 15.1% of the 284 ranking orders. No other dominant ranking order was identified. It seemed that participants' preference towards the design with daylight and view was as evident as their dislike of the design with blue lighting, compared to the baseline design.

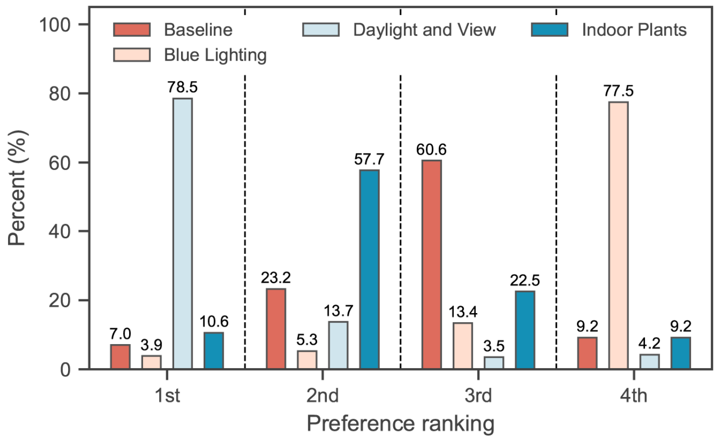

Figure 3. The distribution of preference ranking of the four indoor designs.

4. Discussion

This study examined and compared the influence of two biophilic design strategies and blue lighting on peoples' impressions of an office environment. Through an online survey, responses from a large sample were obtained. The result shows that the biophilic design had a significantly positive impact on space perception, compared to a baseline design. This finding is consistent with previous studies [14,16,41,42,71]. However, blue lighting showed a negative influence on how the office was perceived.

4.1. Comparison between the Two Biophilic Strategies

In this study, the influence of two common biophilic design strategies on people's subjective impression of an office was investigated. Specifically, the office with daylight and access to an outdoor view was compared to the same office with indoor plants. This result shows that access to daylight and view outperformed indoor greenery in all the examined perceptual categories, especially in making the office space appear brighter, more spacious, and more comfortable. However, providing daylight and view access is not always feasible in existing spaces without windows and sometimes can be costly. In these circumstances, it is more practical to employ other design strategies that can create a satisfying environment. This research shows that indoor plants significantly improved participants' perception of the simulated office. In particular, the office with indoor plants was perceived to be more lively, interesting, cheerful, appealing, and brighter than the baseline office. Notably, adding plants made the office appear brighter compared to the base case, suggesting that participants' brightness perception is not only altered by the intensity of light. This result is consistent with the finding in a previous study [72], reporting that people's subjective impression of interior space on daylight brightness satisfaction was influenced by other design factors. Future studies conducted in real offices are required to further support this finding.

4.2. Blue Lighting

Most previous studies on blue lighting suggest that it has a positive impact on people's alertness, cognitive performance, and emotion through a non-visual pathway [26,29–31,34–36], and these effects do not necessarily rely on stimulating the melatonin pathway [37–39]. Despite these potential benefits, blue lighting was found to adversely impact participants' impression of an office in this study. The impact was statistically significant for almost all the perceptual attributes, except for calming. This result seems to be contradictory to the findings of most previous studies that investigate the effects of interior color on subjective impression, suggesting that cool colors such as blue would evoke pleasant, peaceful, and comfortable perceptions [43,58–61]. Similarly, it does not align with Lee's study [68], reporting that blue lighting had significantly higher ratings of attractiveness, comfort, pleasantness, and relaxation compared to other colored lighting. In addition, the result seems to conflict with the findings from two previous studies that suggest blue lighting performed better than white lighting in post-stress relaxation [66] and mood enhancement [27]. A possible explanation is that the saturation and brightness of the blue color matter. It has been reported that the brightness and saturation of a color can influence participants' perceptions and feelings [73]. Typically, a monochromatic blue color is tested in the literature. In this study, we mimicked the blue lighting condition in the field study by Kuijster et al. [27] to simulate a realistic scene. The variation in the saturation and brightness of the perceived blue color might account for the variation between our observation and previous findings. It is important to also note that the overall brightness of the image with blue lighting was slightly lower than the other three, which could be a major confounding factor. An in-depth discussion of this limitation is presented in the following subsection. Another explanation could be that the blue color was compared to the baseline white color in our study, while in the literature it was usually compared to other monochromatic colors.

Meanwhile, this study supports the findings from some studies that suggest lighting of neutral color is perceived better and/or preferred compared to colored lighting [63,64,69]. Specifically, a white office was perceived as more spacious and pleasant than a blue-green office and a red one, as reported by Kwallek [63]. In another study, the authors found that white was the most preferred office color, compared to the other eight monochromatic colors including blue [62]. Similarly, in a most recent study that examined the effect of glazing and the visual perception of daylight, glazing of a neutral color was preferred over blue glazing and orange glazing [69]. As indicated by Kwallek et al. [62], these observations might be explained by social expectations, governing that white is the most "appropriate" color for an office interior. Future studies in other types of interior spaces (e.g., residential homes, hospitals, and schools) are required to confirm this assumption.

4.3. Limitations

As a pilot study, there are a few limitations. First, due to the method used (online survey with computer renderings), the presentation of the interior scenes could vary between participants. The overall brightness and contrast of all scenes can be different, and the saturation of the image color can vary, depending on the settings of participants' monitors and their surrounding luminous environments. However, according to a study on the validation of an online protocol for evaluating the luminous environment [74], bias related to the perceived brightness and contrast of the display and the brightness of the surrounding area can be removed by increasing the number of subjects. The researchers believe that our study's sample size of 284, which is much larger than the recommended 100 subjects, should be sufficient to eliminate this bias. Another relevant limitation is that the lighting condition, such as illuminance in the space, was not characterized due to the use of computer renderings. While using more advanced simulations or immersive tools such as virtual reality may overcome this limitation, it would be more difficult to collect sufficient data for meaningful statistical analyses. There is always a compromise no matter which method is selected. Nevertheless, one method cannot replace but supplements the other. We intend to repeat the same test using virtual reality and conduct physical experiments in future studies.

Another major shortcoming is how the renderings were generated. After creating the baseline scene, the color of the lights was changed from white to blue to mimic the lighting condition in the field study by Kuijster et al. [27]. Due to the variations in color perception, i.e., green light contributes the most to the intensity perceived by humans, and blue light the least, the scene with blue lighting naturally appeared darker than the baseline. The image with blue lighting was darker than the baseline even though we had increased the intensity of the blue lights in the rendering to match it with the baseline. Similar problems occurred when we generated the other two scenes by adding plants or daylight to the baseline scene. To summarize, the actual brightness of the lighting cannot be accurately controlled or estimated due to the limitation of using computer-generated images. We calculated the relative luminance [75] of each pixel (Equation (4)) using the linear RGB components [76] and averaged the value for each image. As indicated in Table 4, all the other three images had a lower average relative luminance than the baseline. The variation between the image with the daylight and the baseline is small (30.5 vs. 31.0). However, this variation is much larger for the image with plants and the one with blue lighting. Since brightness could influence how the simulated offices were perceived, the variation in the actual brightness of the four images could be a confounding factor. This could be a major limitation of this study. However, we can see that the image with plants had significantly higher ratings than the baseline in almost all the examined attributes (including brightness), even though its relative luminance was lower. This observation indicates that the actual brightness might not have been the primary factor that determined subjects' perception of the image, since lower luminance is generally considered to negatively impact how interior space is perceived [67]. This finding is consistent with a previous study reporting that merely changing the color of the image could alter people's satisfaction with the brightness while keeping the illuminance constant [72]. Similarly, in the study of glazing color [69], daylight perception was better with the orange glazing compared to the neutral one, even though the illuminance with the orange glazing was lower. These studies indicate that the effect of color might be dominant compared to the effect of brightness if the variation between brightness is not too large. Preliminary results from one of our ongoing studies also show that people's perception of colored lighting was not altered if the relative luminance of two scenes varied by 30%. This variation in brightness is greater than the largest variation in our study, which is 18.4% between the baseline and the blue lighting design. Therefore, it is reasonable to assume that the variation of brightness between different scenes does not alter or have a significant impact on the results.

Table 4. Relative luminance of the four images.

Image of Simulated Office	Average Relative Luminance
Baseline	31.0
Blue lighting	25.3
Plant	28.6
Daylight and view	30.5

$$L = 0.2126 \times R + 0.7152 \times G + 0.0722 \times B \quad (4)$$

where L is the relative luminance; R = linear R value; G = linear G value; B = linear B value.

Lastly, the generalizability of our results is limited for several reasons. One is that the majority of our participants were young adults, which does not accurately represent the overall population. Another limitation is that the variety of each biophilic design was not considered, such as the amount of greenery, dynamics of daylight, and type of view to the outside. It is possible that designs with different details would lead to varied results. For instance, offices in densely-built zones may be perceived as less positive than the baseline due to an obstructed view. However, it should be noted that it is difficult or even impossible to incorporate these varieties in one single study. For example, indoor daylighting conditions are influenced by multiple factors, such as weather conditions, building geometry, and orientation, the layout of the furniture, etc. Moreover, there are temporal variations due to the seasonal and daily changes in daylight. While it is beyond the scope of this pilot study which aims to outline avenues for further investigations, future studies on how these varieties can be fully considered and reasonably represented are needed. Third, the results of this study are limited to the setting of a private office. More research is required to extend the research to other indoor settings, such as open-plan offices, residential houses, classrooms, etc. Lastly, this study only focused on participants' short-term subjective evaluation; their long-term assessment and physiological measures can be examined in further experimental exploration.

5. Conclusions

This study described the first investigation on the comparison between two distinct interior design strategies: biophilic design and colored lighting. Previous studies indicate that both strategies could have physiological and psychological positive effects on people. However, how their effects compare had not been investigated. This study aimed to address this research gap by examining and comparing people's impressions of two common biophilic design strategies and blue lighting. Using an online survey, subjective evaluations of four simulated interior scenes from 284 participants were collected, including ratings on eight perceptual attributes and preference rankings. Four different design interventions were tested in this study: a baseline office space with conventional white lighting, an office space with blue lighting, a biophilic design with plants, and a biophilic design with daylight and view. As expected, the statistical analysis showed that the biophilic design with daylight and view had the highest ratings on all the perceptual attributes compared to the baseline. It was also the most preferred design of the four alternatives. This result is supported by numerous studies in the literature that have confirmed the benefits of daylight and view access. It is worth noting that adding plants to the office significantly improved subjects' ratings in most of the examined attributes (except for spaciousness). These effects were lower but comparable to that of providing daylight and view. In terms of participants' preference, the office with plants was ranked second. Providing access to daylight and view is not always feasible and sometimes this design strategy can be challenging and costly. Our study suggests that having indoor plants could be a potential alternative in such environments. This could be an effective strategy for spaces devoid of windows, such as underground or basement spaces. Experimental studies are encouraged to further validate our findings. In addition, long-term observations and objective measures can be applied for a more comprehensive investigation.

Existing studies support the non-visual effects of blue lighting on improving alertness, cognitive performance, and emotional state. Some of the studies on ambient color also report that blue color could evoke pleasant, peaceful, and comfortable perception, however, the findings are not conclusive and consistent. As people's impression of a simulated office with blue lighting was investigated in this study, it was found that it had lower ratings in all the perceptual attributes compared to an office with white lighting. These effects are statistically significant except for calming effects. This design was also the least preferred according to subjects' preference rankings. There are several possible explanations for the discrepancy between our findings and the findings that have been reported in the literature. One might be that the brightness and saturation of the blue color we used were different from previous studies. In addition, instead of comparing blue with other monochromatic colors in most existing studies, we compared blue with neutral white. In addition, the image with blue lighting was slightly darker than the one with white lighting due to the limitation of using computer-generated images and the intention to mimic a realistic scene. This could be a major confounding factor. Future studies, especially experimental research, are needed to address this limitation.

The specific results of this study expanded the existing knowledge on the comparison between the effects of two common biophilic design strategies and blue lighting. Particularly, biophilic design outperformed blue lighting in terms of ratings on eight perceptual attributes and preference ranking. Additional studies with a wider range of stimuli that involve the general population are required to investigate the validity of the presented findings under different indoor settings. Further research is encouraged to investigate the replicability of these results in a real environment.

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