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Can Daylighting Instinctively Receive More Acceptance Than Artificial Lighting at Workspaces?

New Evidence from a Field Experiment in Beijing

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ABSTRACT: This study presents an experiment on how the combination of daylighting and artificial lighting can affect participants' alertness, mood, and visual comfort in a full-scale office in Beijing, China. This experiment was conducted during a spring period (19th April ~ 17th May 2019). Research methods included lighting (Inc. spectrum) measurements, KSS (Karolinska Sleepiness Scale) alertness evaluation, PANAS (Positive and Negative Affect Schedule) mood survey, and self-reported satisfaction survey. Key findings are as follows: 1. When a proper lighting condition was achieved based on visual and circadian performances, increasing daylighting levels would significantly reduce negative mood while decreasing the level of alertness. 2. The artificial lighting could be still required to achieve visual comfort and a proper level of alertness, even when a high level of daylighting is available. 3. There might be an upper bound of illuminance for human non-visual performances at workspaces, including alertness and mood.

KEYWORDS: Integrated lighting solution, Alertness and mood, Self-reported satisfaction, Workplace, Beijing

1. INTRODUCTION

Several experiments have exposed that there are significant effects of daylight on occupants' performances in an indoor environment, including visual and colour comfort, alertness, mood, and work productivity [1, 2, 3]. Recently studies of the impact of daylight on office workers' performances have received increasing attention in Europe and North America. A field study in ten Dutch office buildings [4] found out a significant link between occupants' visual comfort and wellbeing and the configurations and installations of the external windows, which could deliver daylighting and view. An on-site experiment conducted in Switzerland also showed that daylighting can improve office occupants' visual performance, mood, and alertness [5]. Another American investigation found that occupants' sleep quality and overall health can be improved with more exposure to daylight at workspaces [6]. In addition, a series of surveys in American office buildings in both summer and winter periods enhanced that daylight can apparently improve mood and sleep quality of office workers [1, 7]. Based on on-site lighting measurements and subjective assessments, Figueiro & Rea [1] recommended that more investigations would be continuously required in order to clarify how daylight regulates sleep and mood among office workers. All the findings above indicated that a workspace with more daylight expose can receive higher occupants' preference in terms of both visual and non-visual response.

However, in a real space with both daylighting and artificial lighting available, effects of the integrated lighting on visual comfort and non-visual aspects including mood, alertness, and sleep quality tend to be more complicated. Using questionnaire a French study first investigated the response among office workers to different amount of daylighting or artificial lighting [8].It was found that occupants tended to choose lower artificial lighting levels when daylight was bright, with an aim to use more daylight for supporting work. By using computer simulations in a small office with photosensors under various daylighting conditions, Kim and Mistrick proposed a method to integrate daylight with artificial light and developed an algorithm of lighting control to achieve visual comfort and reduce energy consumption [9]. Furthermore, from the perspective of the integration between daylight and artificial lighting, a Japanese study examined the visual harmony between daylight from the window and artificial light from the ceiling using a scaled room model [10]. Achieved results showed that daylight and artificial lighting could be harmonized through properly designed illuminance distributions. Recently a series of studies conducted by environmental psychologist explored the natural preference with the occurrence of daylight and artificial light using online questionnaire [11]. It was suggested that beliefs regarding effects of light on health and concentration may mediate the naturalness-attitude relationship, confirming the instrumental motives behind the natural preference for daylight. Thus, due to the development of artificial lighting controls and increasing studies on non-visual effect of lighting, the integrated application of daylight and artificial light has again attracted attention. According to an opinion on daylighting standard and design [12], two key questions were raised as '(1) What makes a room appear daylit? (2) If a room is lit by a combination of daylight and electric lighting, what is the optimum balance of illuminance between the two sources?'. Several studies above [8-11] have just adopted simple methods, such as questionnaire, computer simulation or scale model, whereas few human experiments in a real space were conducted to explore the interaction effect between daylight and artificial light. Apparently, the lighting design at a workspace is still challenging researchers and practitioners in terms of visual perception, human psychological and physiological performances, especially when using both daylight and artificial light.

This article presents an on-site human experiment in an office lit by the combination of daylight and artificial lighting, aiming to answer if daylight can always be accepted as the first solution based on occupants' alertness, mood, and self-reported satisfaction.

2. MATERAILS AND METHODS

2.1 Workspace and participants

From 19th April to 17th May 2019, this experiment was conducted in an office building (Figure 1) in Beijing (Lat: 39.90° N, Long: 116.41° E). Figure 2 gives room plan and internal layout, dimensions, and window position. This room has a dimension of 7.6 × 4.3 × 3.0 m and the surface reflectance of 0.29 (floor), 0.90 (wall), and 0.90 (ceiling). Only one east-facing side window is available for daylighting and view. This east-facing window has the double glazing with a total visual transmittance of 0.78. Its thermal properties include 840 J/(Kg.K) for specific heat Capacity, 0.16 W/(m.K) for thermal conductivity, and 2.211 W/(m^2.K) for U-value. As displayed in Figure 3, the window is composed of two large components (3 x 1.2 m) and three small openable components (0.8 x 1.2 m). Several sitting positions were used for participants in the experiment, such as B1-6 (two workstations marked by the blue dash line).

Twenty-six participants were recruited from university students [age: 20.94 (±1.61) years; gender: male (13), female (13)].

Figure 1: Views of the workspace used for the experiment.

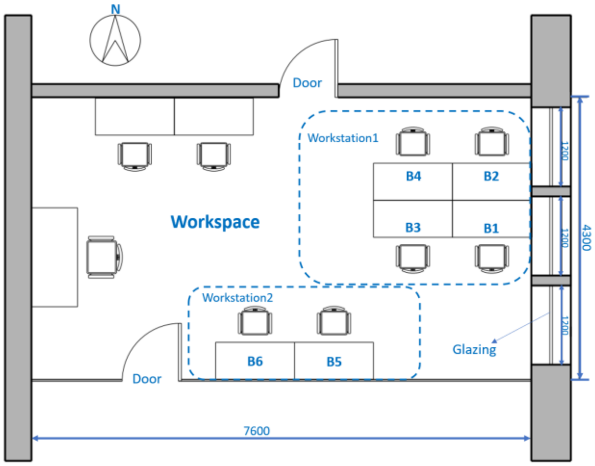

Figure 2: Layout of the workspace used for the experiment.

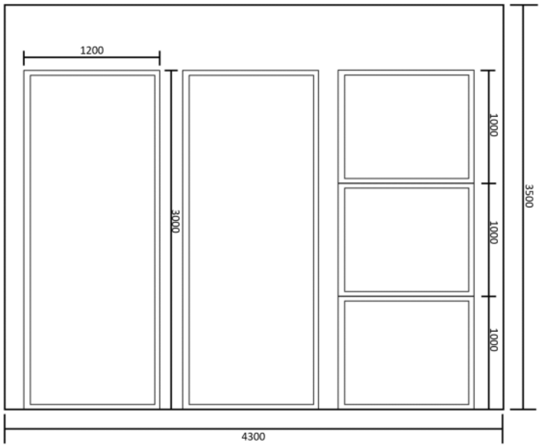

Figure 3: Dimensions and configurations of the window.

Both artificial lighting and daylighting were used during the experiment. The artificial lighting can be adjusted in terms of illuminance and CCT through a local control system called TE-LIG0001. During the experiment, the illuminance produced by the artificial system at the workplane has a range of 15.6 lx to 153.7 lx, while CCT produced by artificial lighting was kept on a constant value of 5200K. Thus, the variation of light colour was only produced by the daylight from the side window.

2.2 Lighting measurement and Circadian Stimulus (CS)

Lighting was measured by a Spectral meter and several wireless lighting sensors to achieve values of illuminances at the table and near participant's eyes (lx), the light spectrum, and CCT (K). The lighting measurement was conducted every 5 minutes automatically. The measurement positions were at participants' working area on the table, and at the vertical plane near participant's eyes with a height of 35±5 cm above the table. The height could be changed according to the actual occupant's eyes position by using an adjustable stand. Thus, based on the measured data, Circadian Stimulus (CS) of ambient light can be calculated using the method in the reference [13]. The key algorithm is as follows (1):

$$\mathrm{CS} = 0.7 - \frac{0.7}{1+\left(\frac{CL_A}{355.7}\right)^{1.1026}} \tag{1}$$

Where CL_A is circadian light, which means irradiance weighted by the spectral sensitivity of the retinal phototransduction mechanisms stimulating the response of the biological clock.

CS ranges from 0 to 0.7. The '0' value means the threshold for circadian system activation whilst the response saturation will be achieved at the value of '0.7'. CS is directly proportional to nocturnal melatonin suppression after one-hour exposure (0% to 70%). According to a field study in offices [14], CS = 0.3 has been recognized as the minimum requirement to reduce sleepiness and increase vitality and alertness of workers.

2.3 Measures: alertness, mood, and self-reported satisfaction

During the experiment, participants were asked to complete an assessment of alertness using the Karolinska Sleepiness Scale (KSS); while the Positive and Negative Affect Schedule (PANAS) was adopted as the mood measure including positive and negative affect [i.e. PANAS (p) and PANAS (n)]. In addition, a self-reported VAS (visual analogue scale) questionnaire was applied at the same time to assess satisfaction and visual performances of participants. Nine questions (Q1-9) were used, including comfort, attractiveness, colour appearance, brightness, glare, appearance of objects, acuity, brightness fluctuation, and light colour fluctuation.

2.4 Procedure

Four sessions in each testing day were used as follows: 08:30-10:00, 10:00-11:30, 13:30-15:00, and 15:00-16:30. Tasks at the start and the end of each session were displayed in Figure 4.

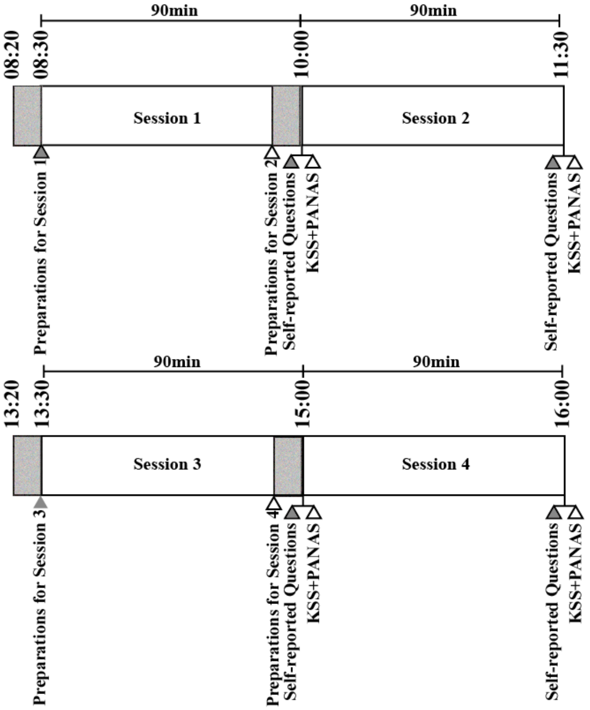

Figure 4: Experimental procedures in this study

The mode of artificial lighting was set before 08:10 in each testing day according to the experiment schedule. As presented in Figure 4, participants will arrive at the room 10 minutes before attending the sessional experiment. During each session, participants were asked to complete the self-reported VAS questionnaire, KSS questionnaire and the PANAS survey at the end of the session.

3. RESULTS

To quantify the amount of daylight and artificial light used during the experiment, two indicators are defined as follows: E_{D+A} is total vertical illuminance measured at eyes with both daylighting and artificial lighting, while R_D is the ratio of vertical daylight illuminance (E_D) at eyes over E_{D+A}. A Spearman correlation analysis was performed between R_D and the feedback of KSS, PANAS and self-reported questionnaire. All significant main effects were achieved when $p \leq 0.05$ or $p \leq 0.01$. IBM_SPSS (v24) was the statistical package used for all analysis in this study.

3.1 Frequencies of illuminance, CCT and CS values

Figure 5 displays frequencies of illuminance near participants' eyes across the whole experimental period. The mean illuminance is 653.84 lx, while 75% of the measured illuminance is above 300 lx and 48% of the values is larger than 500 lx. In general, this office during the experiment has received a relatively high lighting level, which was supposed to be adequate according to the need of visual functions.

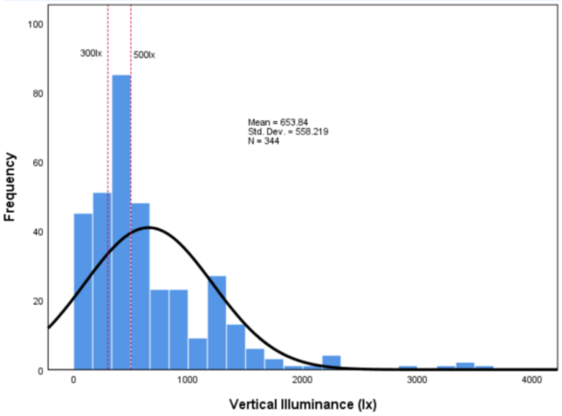

Figure5: Frequencies of measured illuminance near the eyes.

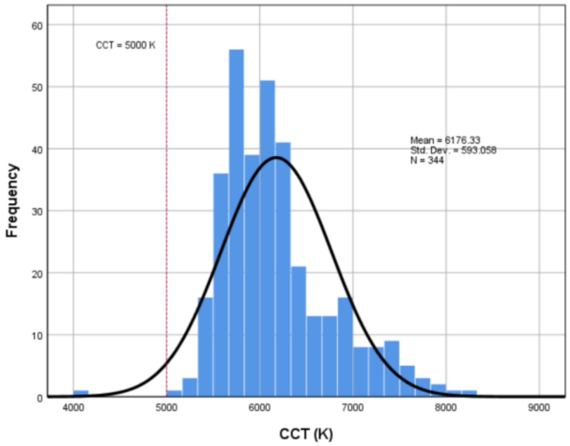

Figure6: Frequencies of measured CCT of light in this space.

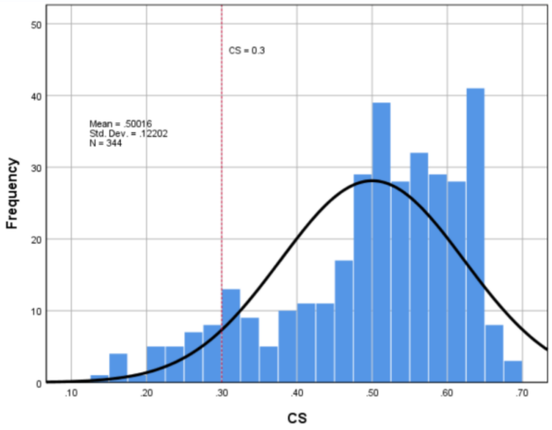

Figure 7: Frequencies of measured CS of light in this space.

Figure 6 and 7 show frequencies of CCT and CS values measured near participants' eyes during the experiment. 97% of the CCT values are above 5000 K, whilst the mean CCT is 6176 K. Since the CCT produced by the artificial light was fixed at 5200K, it can be concluded that the overall CCT was mainly determined by the daylight. Moreover, the mean CS is 0.5. Thus, 91% of the measured CS values are above the threshold of 0.3 [1], which indicated a higher level of circadian stimulus can be achieved at most of testing period. The lighting condition in this office can significantly take positive effects on participants' circadian systems.

3.2 Effects of illuminance (day/artificial lighting) on KSS and PANAS

The Spearman correlation analysis was conducted between E_{D+A}, R_D and scores of KSS and PANAS. As given in Table 1, there is significant correlation between R_D and KSS / PANAS(n) scores, indicating that increasing the ratio of daylight illuminance (R_D) can significantly reduce alertness level (KSS) and negative mood [PANAS (n)]. However, no significant correlation can be found between E_{D+A} and KSS / PANAS scores.

Table 1: Spearman correlation analysis between E_{D+A}, R_D and scores of KSS, PANAS (p & n).

	Correlation coefficient (Spearman's rho)		
	KSS	**PANAS (p)**	**PANAS (n)**
E_{D+A}	0.016	0.020	-0.103
R_D	-.111*	-.053	-.165**

**. Correlation is significant at the 0.05 level (2-tailed).*
***. Correlation is significant at the 0.01 level (2-tailed).*

Given that the illuminance level could affect occupants' response, the overall experimental data were divided into four ranges according to the illuminance near participants' eyes, such as below 300 lx,300 -500 lx, 500-1000 lx, and above 1000 lx. Then, the spearman correlation analysis was separately tested in four sub-datasets.

Table 2: Spearman correlation analysis between E_{D+A}, R_D and scores of KSS for different illuminance ranges.

	Correlation coefficient (Spearman's rho) -KSS			
	<300 lx	**300-500lx**	**500-1000 lx**	**>1000lx**
E_{D+A}	-.005	-0.011	0.084	-0.347**
R_D	-0.26*	-0.204**	-0.113	-0.266*

**. Correlation is significant at the 0.05 level (2-tailed).*

***. Correlation is significant at the 0.01 level (2-tailed).*

For KSS, Table 2 shows that significant negative correlation could be found between R_D and KSS score among three illuminance groups except for the range of 500 - 1000 lx. For the illuminance < 500 lx, the correlation well corresponds to the results in Table 1 in that occupants tend to feel relaxed when the daylight proportion increased. Interestingly, when illuminance was above 1000 lx, there was significant correlation between E_{D+A} and KSS score, indicating that occupants would become more relaxed and even feel sleepy when exposed to excessive daylight.

As regards PANAS, significant correlation could only be found when illuminance is between 300 lx and 500 lx (as shown in Table 3). With the increase of illuminance from 300 lx to 500 lx, occupants would achieve higher positive mood. Similarly, negative mood would be reduced if R_D increases. These results could be explained by the facts: vertical illuminance below 300 lx could not meet the basic requirement to active non-visual system, while occupants' non-visual system tend to be insensitive to the high illuminance (above 500 lx). Thus, with the vertical illuminance ranging from 300 lx to 500 lx, occupants preferred a relatively higher illuminance to help improve mood.

Table 3: Spearman correlation analysis between E_{D+A}, R_D and scores of PANAS (p & n) for different illuminance ranges.

Correlation coefficient (Spearman's rho) -PANAS					
		<300 lx	**300-500lx**	**500-1000 lx**	**>1000lx**
PANAS(p)	**E_{D+A}**	0.211	0.193*	-.042	-.082
	R_D	0.043	-.026	-.081	-.017
PANAS(n)	**E_{D+A}**	-.035	-.129	0.027	-.171
	R_D	-.214	.278**	-.065	-.053

**. Correlation is significant at the 0.05 level (2-tailed).*

***. Correlation is significant at the 0.01 level (2-tailed).*

3.3 Effects of illuminance (day/artificial lighting) on self-reported satisfaction

The spearman correlation analysis was also performed for nine self-reported questions. Table 4 shows that only the feedback of two questions is significantly linked with E_{D+A} (Q4 & 9) or R_D (Q1 & 2). Increasing E_{D+A} can lead to a brighter space, while lowering the perception of light colour. On the other hand, increasing the ratio of daylight illuminance could reduce comfort level and light attractiveness.

Table 4: Spearman correlation analysis between E_{D+A}, R_D and feedback of self-reported questionnaires.

Correlation coefficient (Spearman's rho)					
	Q1	**Q2**	**Q3**	**Q4**	**Q5**
E_{D+A}	-0.032	-0.021	-0.012	.182**	0.035
R_D	-.133*	-.109*	-0.105	0.050	0.020
	Q6	**Q7**	**Q8**	**Q9**	
E_{D+A}	0.025	0.100	-0.077	-.124*	
R_D	-0.046	-0.024	-0.049	-0.039	

**. Correlation is significant at the 0.05 level (2-tailed).*

***. Correlation is significant at the 0.01 level (2-tailed).*

Similar to Section 3.2, spearman correlation analysis was also conducted here in terms of four illuminance ranges. In Table 5, significant results were just found for two illuminance ranges, including < 300 lx, and 300-500 lx. To be specific, R_D was negatively correlated to Q1-comfort, Q2-attractiveness, Q3-color appearance, Q4-brightness, Q6-appearance of objects, and Q7-acuity. It seems that with vertical illuminance < 500 lx, the larger R_D values tend to make the room feel more uncomfortable, unattractive, and unnatural, whilst occupants would feel less bright and the object looks to be stiffer and dimmer. This result might conflict with the common knowledge that we prefer to have more daylight at a normal workspace. Given that at most time the experiment was conducted with a sufficient lighting level (contributed by daylight and artificial light), participants' feedback might support that a higher proportion of artificial lighting will be beneficial to the visual performance in the integrated lighting environment. On the other hand, high proportions of daylight may negatively affect occupants' visual functions. Most importantly, there is an apparent difference between light incident paths (daylight from side window and artificial light from ceiling). This could be used to explain the human response to the two light sources when a higher lighting level was achieved.

Table 5: Spearman correlation analysis between R_D and feedback of self-reported questionnaires.

Correlation coefficient (Spearman's rho) -Self-reported questionnaire				
	<300 lx	**300-500lx**	**500-1000 lx**	**>1000lx**
Q1	**-.430****	**-.260****	-.039	-.098
Q2	**-.293****	**-.268****	-.003	-.062
Q3	**-.253***	**-.172***	-.170	.041
Q4	**-.253***	**-.160***	-.123	.115
Q5	.014	-.093	-.056	-.125
Q6	**-.267***	**-.228****	.057	-.080
Q7	**-.213***	**-.163***	-.118	-.116
Q8	-.023	-.080	-.002	-.006
Q9	-.106	-.128	.128	.047

**. Correlation is significant at the 0.05 level (2-tailed).*

***. Correlation is significant at the 0.01 level (2-tailed).*

4. DISCUSSION AND CONCLUSION

First, when a proper lighting condition was achieved based on visual and circadian performances, increasing daylighting levels would reduce negative mood, while the alertness level could be decreased at the same time. Thus, even though the daylight may help improve office workers' mood and reduce stress, the increased body relaxation level might lead to lower alertness. A field study [8] found that the low-level artificial lighting was preferred by occupants when daylight was too bright. Visual comfort could be the direct reason for explaining this choice. However, our study could expose another proof that office workers would keep a proper level of alertness to achieve normal work productivity by using controllable artificial lighting. Therefore, it is worthy of reconsidering and further exploring the visual and non-visual effects of daylight on occupants' performance under a high lighting level.

Second, at a workspace with a higher level of daylight availability through the side window, the artificial lighting could be still required, especially based on an aim to achieve visual comfort. Even though a psychological study [11] pointed out that the human tendency to prefer natural substances over their synthetic counterparts is also operative in the domain of light, some results would still support that the ability to easily control illuminance levels gives electrical lighting a benefit over natural daylight in an office environment [11]. Another study [10] found that artificial lighting from room ceiling could be required to adjust illuminance distributions caused by the daylight from side windows according to the visual harmony of occupants. Thus, it seems that the key aim to apply daylight would be targeted at the benefit of non-visual effects including mood and alertness, while the advantage of artificial lighting is to deliver proper visual functions.

Third, this study has supported that there might be an upper bound of illuminance for human non-visual performances. In this experiment, when the vertical illuminance near participants' eyes was above 500 lx, no correlations were found between the lighting levels and KSS scores, PANAS (p or n), and self-reported questions. Previous studies have found that if a higher CS level (≥0.3) can be achieved, the colour of daylight transmitted through the glazing would not significantly affect human's alertness, mood, and visual comfort [2, 3]. Exploring the upper bound may be useful for strategy development of both health lighting and energy efficiency.

Several limitations can be found. 1. The experiment was conducted in a specific office, and within a relatively short period (30 days). 2. All tests were achieved based on higher lighting levels according to visual and non-visual performances. Results did not include data achieved under low-level lighting conditions. 3. A higher proportion of daylight amount was prevalent across the experiment. The data might not be able to reflect the situation of a higher amount proportion of artificial light. More studies will be continuously carried out.

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