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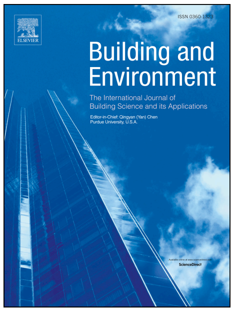

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Glazing Type (Colour and Transmittance), Daylighting, and Human Performances at a Workspace: a Full-scale Experiment in Beijing

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Abstract:

This study presents a human experiment of effects of glazing types (colour and transmittance) on participants' alertness and mood, working performance, and self-reported satisfaction in a full-scale office in Beijing, China. Seven glazing systems were tested in a winter period (17th Nov 2017 ~ 15th Jan 2018). Research methods included lighting measurements, KSS (Karolinska Sleepiness Scale) sleepiness evaluation, PANAS (Positive and Negative Affect Schedule) mood survey, reaction time test (GO/NOGO), and self-reported questionnaires. Key findings are as follows: Circadian Stimulus (CS) can be used as an indicator of alertness and mood in a daylit workspace. If a higher CS level (⩾ 0.3) can be achieved, glazing colour and transmittance would not significantly affect human's alertness and sleepiness. A low CS level (< 0.3) would bring in significant negative mood to occupants. On the other hand, the improvement of occupants' mood would be achieved through increasing glazing visual transmittance and/or decreasing its colour saturation. Self-reported satisfactions show that a preference will be given to the glazing systems with neutral colour and/or higher transmittance in terms of visual performance. It is unknown why the glazing systems with a medium CCT of 4400 K or a higher CCT of 8100 K can deliver shorter response time (RT) and better working performance in a reaction time task. It would be necessary to carry on investigations into the human performances and light colour, especially under daylighting conditions.

Keywords:

Daylighting, Glazing colour and transmittance, Alertness and mood, Working performance, Self-reported satisfaction, Office, Beijing.

1. Introduction

Daylighting is recognized as one critical environmental factor that can significantly affect workers' productivity, overall satisfactions, and health/well-being at workspaces [1, 2, 3]. Studies of the effect of daylighting on human performances are receiving increasing attention in offices. A field survey in ten Dutch office buildings showed that workers' visual comfort and well-being are substantially associated with configurations and installations of external windows (delivering daylighting and view) [4]. A Swiss experiment [5] further demonstrated that occupants' visual performance, mood and alertness can be improved by daylighting. Another American study [6] showed that more exposure to daylight tends to improve sleep quality and overall health of office workers. Furthermore, a series of American office surveys enhanced the importance of daylighting and its capabilities of improving stress, mood and sleep quality of occupants, particularly in winter when the daylight availability is lower [7, 8]. These findings suggested that more emphasis should be placed on providing occupants with more daylight exposure in offices [6].

There is an evident link between colour of light and human performances (mood, alertness, etc.) at workspaces [9, 10]. It has been studied over ten years with artificial lighting. A cross-cultural study [11] indicated that a proper light colour might contribute to positive mood and healthy workspaces. A Swedish study [9] found: 1) Females perceived the light more sensitively than males; 2) For long-term memory, interactions between colour and gender showed that both males and females performed better with warm lighting (3000 K) than white and blue lighting (4000 K and 5500 K), and that women performed better than men with the light of 5500 K. Two American experiments suggested that blue is a calming colour while red can be stimulating in offices [12]. A German survey [13] confirmed that light is the dominant environmental cue for human circadian rhythm and that the light with short-wave length (blue) could be used to entrain circadian clock to specific schedule. However, an American experiment found that the light with long-wave length (red) can apparently increase alertness and task performance in the afternoon, and its alerting effects are stronger than short-wave length [14]. This effect of red light has been also proved effective in early morning [15]. It thus seems that the red light can be applied to improve human performance in daytime [10]. Segal et al. [16] amended these findings [14, 15] by a conclusion of 'daytime exposure to short- and medium-wavelength light did not improve alertness and neurobehavioral performance'. Furthermore, the 2700 K light can lead to a higher alertness in a reaction time task than the 6500 K light; while subjective sleepiness was not affected by CCT [17]. A Dutch study [18] presented one interesting finding that the light with higher CCT would not be regarded as a normal setting during daytime office hours, since the higher CCT will not benefit human performances according to individuals' affective state, cognitive performance, and autonomic nervous activity in the morning or afternoon. Given the studied above and a review [19], it could be difficult to draw definitive conclusions of the effects of light colour due to the lack of findings that can be used to build up dose-response curves for practical use. In addition, environmental and individual factors might also influence the achieved results [12, 20].

The applications of coated/tinted glass lead to the phenomenon that the coloured glazing can be broadly found in buildings across the world [21, 22, 23]. Their primary functions focuses on adjusting solar gains, and therefore improving thermal and visual performances [23]. However, the impact of such glazing on visual and colour perceptions, and human satisfactions could be critical [24]. An Swedish study [24] found that there were significant differences of subjective perceptions of daylighting and colour between three-pane clear glazing and four-pane coated glazing in a daylit room. This has raised a question of how far we can reduce the transmittance of window for the sake of saving heating energy via increasing fabric insulations [24]. A pilot study using a scale model indicated that the neutral coated glazing with a high visual transmittance would receive more acceptances in Denmark [25]. Another Norwegian study found that coloured coated glazing products in current European market can possibly distort the colour appearances of daylight in buildings [26]. A measurement concluded that it is necessary to find a proper model to justify the colour quality of the light transmitted through different glazing systems [27]. A Canadian study in a scale model indicated that there is a preference for daylight filtered through coloured glazing and that the glazing colour may have a significant effect on human's alertness [28]. This study [28] revealed that the bronze glazing receives more preferences than the blue and clear glazing for 36 Canadian participants. Apparently, it is still necessary to conduct more studies on how the daylight combined with various glazing systems works on human performances, especially with the facts: 1) the number of available human experiments is small; 2) the completed studies have limited climates and human cultural backgrounds, i.e. in North America and Europe.

As highlighted in several studies [2, 29, 30], only limited statistically significant and well-documented scientific proof is available for the relationship between daylight and human health/well-being. Thus, in this article, a human experiment was implemented in an office in Beijing, China. It aimed to use a full-scale workspace to investigate how the daylight combined with various coloured glazing systems affects Chinese participants' alertness, mood, working performance, and self-reported satisfaction across a winter period.

2. Methods and materials

2.1 Laboratory, study design and participants

From 17 November 2017 to 15 January 2018, this study was performed in an office room of School of Architecture in Tsinghua University in Beijing, China (Latitude: 39.9042° N, Longitude: 116.4074° E). The office room has one side window facing south, and four sitting positions including A & C (working places for participants), B and D (for GONOGO test, see section 2.6), and its dimension is 6.3×3.2×3.8 m.

Figure 1. Plan and dimensions of the room studied, and interior views of seven coloured glazing windows.

This office interior has been refurbished before the human experiment was initiated. The ceiling, wall and floor have been painted as matt surfaces. Measured on site by a portable Spectrophotometer (KONICA MINOLTA: CM-2600D), the diffuse reflectances of the room surface are 0.3 (floor), 0.88 (wall) and 0.88 (ceiling).

As shown in Figure 1, the side window has a dimension of 2.3×2.3m, and a two-layer structure. The external layer is composed of single-pane clear glazing and dividers, while the internal layer adopts a removable structure with easily installed/dismantled glazing and dividers. Seven types of glazing were studied including clear, blue, bronze, grey, green, darkblue and red. Figure 1 displays pictures of the interior appearances of them in the room. The first four types are typical products found in current Chinese window market and have been widely used in modern non-domestic buildings. However, other three types were studied based on current practical applications in China, e.g. EC glazing (darkblue), Transparent PV glazing (green or red colour). On the other hand, the use of the three glazing types was due to the fact that they have clearly different spectral distributions from the four typical types (Figure 2). We believe that the seven glazing systems can cover all possible types in terms of glazing colour.

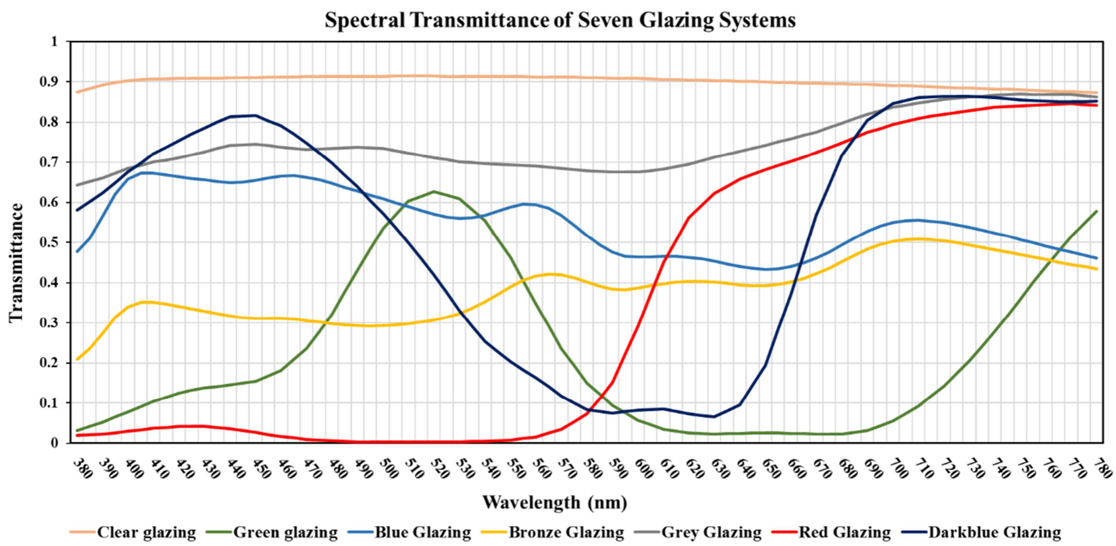

Figure 2. Spectral transmission of seven glazing systems studied in this office (China Academy of Building Research).

The spectral transmissions (Figure 2) and overall visual transmittance (VT) of the seven glazing systems were provided by China Academy of Building Research. Their VT values are 0.91 (Clear), 0.55 (Blue), 0.38 (Bronze), 0.75 (Grey), 0.22 (Green), 0.54 (Darkblue), 0.35 (Red). In order to understand the overall visual transmittance of the two-layer glazing, a luminance meter (KONICA MINOLTA Luminance Meter LS-150) and a neutral grey standard (BIZOE M SIZE: fixed diffused surface reflectance 19%) were adopted to conduct the on-site measurement. Under a stable lighting condition without sunlight (overcast sky), each two-layer glazing was placed between the luminance meter and the grey standard to get the first reading of surface luminance of grey standard (L1); next, the second reading of surface luminance of grey standard (L2) was achieved after removing the two-layer glazing. Then, overall visual transmittances of the seven two-layer glazing systems can be calculated by L1/L2 as follows: 0.66 (Clear), 0.40 (Blue), 0.29 (Bronze), 0.56 (Grey), 0.17 (Green), 0.41 (Darkblue), 0.26 (Red).

A total of 11 participants were recruited from current students at Tsinghua University, with a mean age of 22.27 (±2.95) years, including 6 males and 5 females. No participants have medical and psychiatric diseases and sleep disorders. Each participant attended a seven-day experiment, while only one type of glazing has been tested in each experiment day. During the experiment, the participants were just allowed to carry out regular office work in the room, such as reading, writing, typing, etc. No food and drinks with caffeine or similar content can be taken during the testing day.

2.2 Daylight measurements and Circadian Light

This study was conducted under daylighting conditions. No artificial lighting can be used in the experiment, even if the daylighting level was insufficient to meet the lighting standard at the working plane, i.e. 500 lux according to Chinese building regulation [31, 32]. The lighting condition was measured by a portable Illuminance Colour Spectral meter (SPIC-200), in terms of three types of data: illuminance (lux), spectral distribution and correlated colour temperature (CCT, K). The measured positions were at participants' working area on the table, and at the vertical plane near the participant's eyes with an approximately 35±5 cm height above the table. Each meter reading was recorded every 10 minutes.

Based on light spectral distributions measured near participants' eyes, Circadian Light (CL_A) and Circadian Stimulus (CS) were achieved according to these theories [33, 34]. The two values were adopted as indicators of the nocturnal melatonin suppression due to the spectral response of the human circadian system [34]. Different from the illuminance based on the photopic luminous efficiency function [V(λ)], CL_A is irradiance weighted by the spectral sensitivity of the retinal phototransduction mechanisms stimulating the response of the biological clock [33]. The equations of CL_A calculation are given as follows [33, 34]:

$$CL_A = 1548[\int M_{C_\lambda} E_\lambda d\lambda + (a_{b-y}(\int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k \int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda) - a_{rod}(1 - e^{\frac{-\int V'_\lambda E_\lambda d\lambda}{RodSat}}))],$$

$$\text{If } \int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k \int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda) > 0 \qquad (1);$$

$$CL_A = 1548 \int M_{C_\lambda} E_\lambda d\lambda,$$

$$\text{If } \int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k \int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda) \leq 0 \qquad (2);$$

Where, CL_A is the circadian light. The constant, 1548, sets the normalization of CL_A, so that 2856K blackbody radiation at 1000 lux has a CL_A value of 1000;

E_λ is light source spectral irradiance distribution;

Mc_λ is ipRGC melanopsin sensitivity (corrected for crystalline lens transmittance);

S_λ is S-cone fundamental;

mp_λ is macular pigment transmittance;

V_λ is photopic luminous efficiency function;

V'_λ is scotopic luminous efficiency function;

RodSat is half-saturation constant for bleaching rods = 6.5W/m^2;

K =0.2616, representing the interactions among photoreceptor types. This value has been set so the crosspoint of the b–y (blue-yellow) channel is at 507 nm, consistent with independent estimates of unique green;

a_{b-y} = 0.7000 and a_{rod} = 3.3000, which represent the interactions among photoreceptor types (b-y: blue-yellow channel, and rods).

Thus, CS can be produced via the transformation of CL_A using the following algorithm [34]:

$$\text{CS} = 0.7 - \frac{0.7}{1+(\frac{CL_A}{355.7})^{1.1026}} \qquad (3).$$

CS has a range of (0~0.7). 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%) [34, 35]. As discussed in a field study in offices [30], CS = 0.3 has been recognized as the minimum requirement to reduce sleepiness and increase vitality and alertness of workers.

It could be noted that the method mentioned by Lucas et al. [36] can be another way for evaluating circadian stimulus. However, as mentioned in the review [36], no practical thresholds have been achieved based on the application of five potential photoreceptive inputs to circadian and neurophysiological light responses in humans, such as Cyanopic illuminance, Chloropic illuminance, Erythropic illuminance, Melanopic illuminance, Rhodopic illuminance. Even though this approach can provide with a clear theoretical model to justify the circadian light responses, 'it is not yet possible to predict the non-image-forming impact of a given illuminant based on its intensity and spectral composition' [36]. On the contrary, CL and CS [34] were established as a metric to practically measure the circadian stimulus of light for architectural lighting. Based on a number of human experiments and on-site surveys over 10 years [7, 30], several key thresholds have been found for CS, such as 0.3 (nocturnal melatonin suppression; CS$\geqslant$0.3 can reduce sleepiness and increase vitality and alertness), 0.7 (response saturation of circadian system). Thus, we have selected the CL and CS as a model to predict the circadian stimulus of light in this study. In terms of the measurements of spectrum and illuminances near occupants' eyes, CL and CS have been achieved based on a frequency of 10 minutes to justify the human performance cross the daily working time (see section 3.2).

2.3 Sleep quality assessment: PSQI

The Pittsburgh Sleep Quality Index (PSQI) was applied as a measure of sleep quality and disturbance retrospectively over a one-month period using self-reports [37]. It has been used among a variety of populations and its reliability and validity have been therefore proved. This study adopted PSQI as an instrument of evaluating participants' sleeping quality in order to confirm a normal working schedule before starting the daily experiment for each participant. PSQI is composed of 19 self-assessment questions concerning sleep quality. A PSQI score is achieved in a range of 0~21. Generally, a higher PSQI score tends to display a worse sleep quality. More specifically, various score ranges can be used to justify the sleep quality in the following models: 0~5 (Perfect), 6~10 (Good), 11~15 (normal), 16~21 (bad).

2.4 Alertness measure: KSS

Participants were asked to complete a self-assessment of sleepiness using the Karolinska Sleepiness Scale (KSS) [38]. This study adopted the feedback of KSS to obtain subjective sleepiness and alertness across all daytime experiments with various galzing systems. KSS questionnaire was collected every 45 minutes along with the self-reported satisfaction questionnaire (section 2.7). The scale of KSS ranges from 1 to 9, where 1 = “very alert”, 3 = “rather alert”, 5 = “neither alert nor sleepy”, 7 = “sleepy, but no difficulty remaining awake”, and 9 = “very sleepy, fighting sleep, an effort to remain awake” [38].

2.5 Mood measure: PANAS

The Positive and Negative Affect Schedule (PANAS) was established as a valid mood measure including positive and negative affect [39]. This study used PANAS scales to evaluate participants’ mood influenced by different glazing types and times. The PANAS model contains 10 items relating to positive mood and 10 items for justifying negative mood, and each item has 5 scores as: 1 (very slightly), 2 (a little), 3 (moderately), 4 (quite a bit), and 5 (extremely). Participants in this study were given a task to complete one PANAS questionnaire (20 items) every 90 minutes. Normally, a higher positive mean score would indicate more positive mood, while a higher negative mean score could show more negative mood.

2.6 Reaction time test: GO/NOGO

Given a review [19], the reaction time task can be used as one of important tools for justifying the non-visual effects of light. GO/NOGO, a typical task for testing reaction time, was generally used to measure participants' capacity for sustained attention and response control [40]. In this study, participants’ working performances were tested using a computer GO/NOGO tool.

As suggested in a human experiment [10], each GO/NOGO test of this study lasted around 10 minutes and participants responded to tasks via a computer mouse (sitting positions were displayed in Figure 1). For each test, a smiling or frowning face was presented on a black background every 2-10 seconds. Participants were instructed to take actions as follows: clicking the mouse when smiling face appears; stopping to respond when the frowning face occurred. The occurrence of smiling face will be around 70% of the total test time while only 30% of the time will be allocated to the frowning face. Once the mouse was clicked, the face will disappear and the time from the face 'appear' to 'disappear' will be recorded as the Response Time (RT). If the participant's response time is above 1.0 second, the face will vanish and therefore a 'Miss' will be given. In addition, a 'False Alarm' will be recorded if the participant clicked the mouse before the face appears. Each participant attended a GO/NOGO test every 90 minutes during the daily experiment.

Two standard scores of GO/NOGO, including overall accuracy (OA) and mean response time (RT) [40], were used to measure the working performances of participants. In a human experiment [10], a new value of Tput was proposed to assess data and overall performance throughout one GO/NOGO test. Tput can be calculated by: 100 × (# of valid responses) / (# of total responses) / median of the response times. The higher value of Tput indicates a better working performance. A valid response in the calculation will not include 'Miss' and 'False Alarm'. Tput was used as the third score in this study.

2.7 Self-reported questionnaire

A self-reported questionnaire was adopted in this study to assess the satisfaction and visual performances of participants with various glazing systems and working times. A paper-based VAS (visual analogue scale [41]) was used as a measure for each question (scale range: 0-100 mm).

The self-reported questionnaire (Figure 3) is composed of 10 questions, focusing on lighting levels, visual and colour comfort, pleasantness, attractiveness, visual acuity, and colour naturalness [42, 43]. The first part aims to survey general visual appearance of the office room, including four questions: VQ1, Under this daylighting the overall room appears to be? (0 mm, very unpleasant; 100 mm, very pleasant); VQ2, Under this daylighting the overall room is? (0 mm, very uncomfortable; 100 mm, very comfortable); VQ3, The daylighting makes the room look? (0 mm, very unattractive; 100 mm, very attractive); VQ4, I like this daylighting in this room? (0 mm, not at all; 100 mm, very much). Moreover, the second part is used for assessing the visual and colour appearance at the table area, with six questions: VQ5, The light level of this daylighting at the table seems to be? (0 mm, insufficient; 100 mm, sufficient); VQ6, Have you felt the glare? (0 mm, not at all; 100 mm, unbearable); VQ7, The brightness of this daylighting at the table seems to be? (0 mm, comfortable; 100 mm, too bright); VQ8, The colour of the objects on the table looks? (0 mm, very unnatural; 100 mm, very natural); VQ9, The contour of the objects on the table looks? (0 mm, very clear; 100 mm, very unclear); VQ10, The light colour near the table is? (0 mm, very uncomfortable; 100 mm, very comfortable). These questions were recommended in an office lighting survey [42], while their validity, reliability and feasibility have been investigated or proved in other office lighting surveys [5, 43].

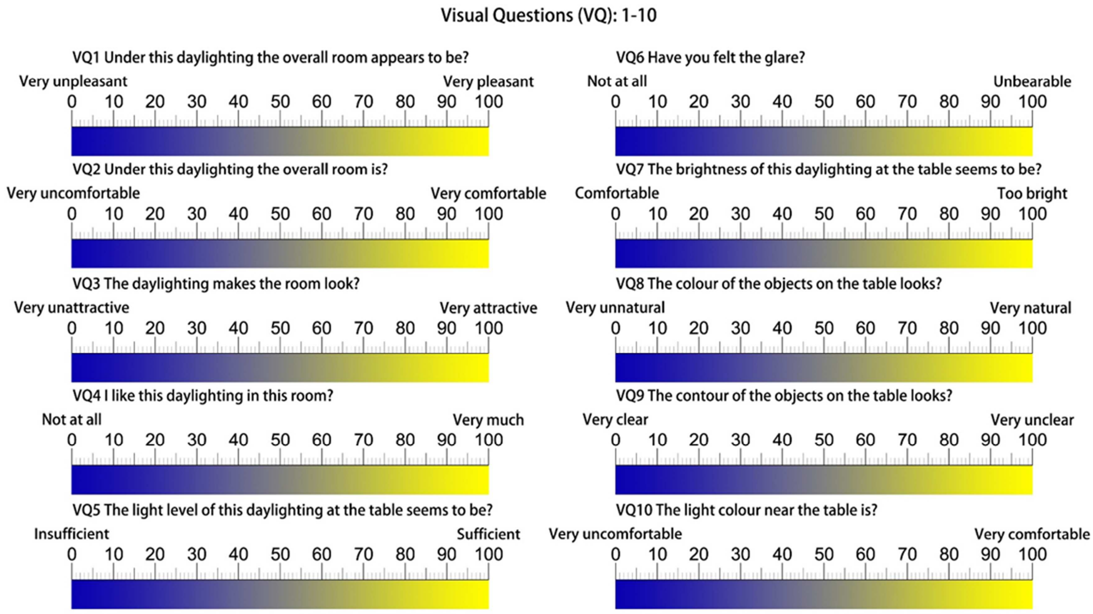

Figure 3. VAS (visual analogue scale) questionnaire for self-reported satisfaction: VQ1-10.

2.8 Protocol

Each participant was required to attend a seven-day experiment during a normal working time (8:30 – 16:00). The daily experiment was divided into two time-slots: 08:30 - 11:30 and 13:00 - 16:00, with a 1.5 hours lunch break in between. In order to control prior light exposure, each participant was asked to start his / her sleep earlier than 23:00 in the evening before the testing day, while a sleep log was used to record participants' sleep time.

As displayed in Figure 4, participants will arrive at the room 20 minutes before starting the daily experiment, and will then fill in one PSQI questionnaire first. During the experiment, each participant was asked to complete the self-reported visual questionnaire (section 2.7) and KSS questionnaire (section 2.4) every 45 minutes, whilst the PANAS survey (section 2.5) and GO/NOGO test (section 2.6) were conducted every 90 minutes. The first survey of self-reported satisfaction and KSS was initiated at 8:30 and then there will be totally 10 copies of each questionnaire in one experiment day. For PANAS survey and GO/NOGO test, the first task was conducted at 10:00, and then each task will be repeated four times per day.

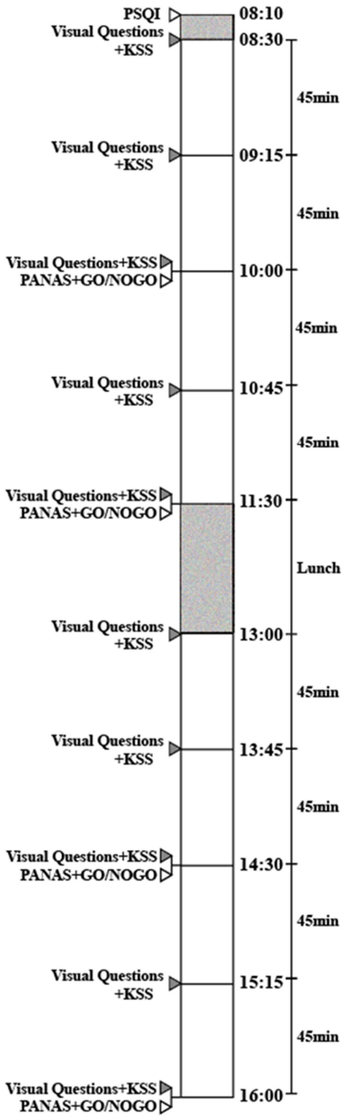

Figure 4. Experiment protocol: The protocol includes collecting self-reported satisfaction feedback, Karolinska Sleepiness Scale (KSS) feedback, and Positive and Negative Affect Schedule (PANAS) feedback, and conducting performance tests (GO/NOGO).

2.9 Data Analysis

As regards the effect of glazing colour and time, a two-way repeated measures of variance (ANOVA) with 'participants' as random factors was performed for the feedback of KSS and PANAS, three GO/NOGO scores (OA, RT, and Tput), and the feedback of self-reported visual questionnaire (10 questions). A Post

Hoc analysis using the Tukey HSD model [44, 45] was further conducted to compare the significant main effects and interactions. The use of Tukey HSD procedure was because of the large number of groups of each independent variable (> 3), as discussed in the reference [44]. All significant main effects were achieved when $p \leq 0.05$. Before initiating ANOVA and Post Hoc analysis, the raw data from each subject, including feedback of KSS, PANAS, self-reported questionnaires, and scores of performance test from GO/NOGO, were first normalized using the MinMax scaling model [46, 47]. This process aimed to minimize unwanted effects of individual differences in term of a given dependent variable [47]. The scaling algorithm was as follows: $X-X_{min} / X_{max}-X_{min}$ (4), where X is the raw value of each assessment item; X_{max} and X_{min} are the maximum and minimum values of each item respectively. IBM_SPSS (v24) was the statistical package used for all analysis in this study.

3. Results

3.1 PSQI-sleeping assessment

PSQI score from all participants during the experiment have achieved a mean (±SEM) of 4.84 (±1.93), which can indicate an overall ‘perfect’ sleep quality (score < 5) according to the thresholds [37]. The highest and lowest PSQI scores were found as 9 and 0 respectively. This showed that all participants have a proper sleeping quality (‘Perfect’ or ‘Good’) during the night before attending the experiment. To be more specific, the participants have received good sleep consistency and efficiency without any sleep disorder. In addition, no participants have used any sleeping medicine during the experiment. Therefore, it can be concluded that the sleep issues did not affect participants’ performances across all experiments.

3.2 Daylight Illuminance, CCT and Circadian Stimulus

In Table1 and 2, mean (±SEM) values of the vertical illuminance (VE) near participants’ eyes and the horizontal illuminance (HE) at the working area of the table are given in terms of times and glazing types. Most of the times, the clear, blue and red glazing have higher illuminances than other types, with overall mean VE values as 1500.7 (±219.1) lux, 1675.8 (±237.3) lux and 1790.8 (±262.5) lux respectively, and overall mean HE values as 1648.9 (±206.1) lux, 1097.6 (±133.8) lux and 1591.5 (±200.9) lux respectively. On the other hand, the lowest illuminances (overall mean) can be found with the grey glazing as: VE = 296.1 (±40.0) lux, HE = 248.04 (±25.97) lux. Overall mean vertical illuminances of bronze, darkblue and green glazing are 794.3 (±133.8) lux, 507.2 (±70.0) lux and 683.5 (±98.1) lux, while 635.9 (±76.6) lux, 505.4 (±82.9) lux and 553.4 (±58.1) lux are overall mean horizontal illuminances of them. Apparently, in comparison to glazing visual transmittance, external sky conditions have taken more effects on the indoor daylight illuminance. From 11:30 to 14:30 and for most glazing types (excluding grey), mean illuminances are found above 400 lux (VE) and 300 lux (HE), whilst the time slot of 13:00 -- 13:45 has a much higher illuminance (> 1000 lux). In the morning (08:30 - 09:15) and the late afternoon (15:15 - 16:00), all glazing types deliver a relatively lower illuminance. In general, for all glazing types, mean illuminances peak at the period of 11:30 ~ 14:30.

As for the mean CCT of light near participants' eyes (Table 1), there are significant differences between glazing systems during the daily eperiment from 08:30 to 16:00. The darkblue and green glazing have higher overall mean CCT [8665.1 (±25.5) K and 8148.4 (±30.1) K] than other types, which could lead to a 'very cold' lighting atmosphere. It is normal that the lowest overall mean CCT of 1268.8 (±9.6) K occurs with the red glazing. The blue glazing has an overall mean CCT of 5628.2 (±33.6) K, which can be considered to deliver a 'cool' atmosphere. Furthermore, the use of bronze, grey and clear glazing can give rise to overall mean CCT values between 3900K and 4500K, indicating a 'warm white / cool white' atmosphere.

Figure 5 displays mean values of CS near participants' eyes with varying times and glazing types. In comparison to other glazing types, the darkblue glazing has very low CS values (< 0.3) across all times, demonstrating that its application would bring in a lower effect of light on the nocturnal melatonin suppression [34]. Such an effect was achieved via the combination of incident daylight illuminances and the spectral transmittance of glazing [34]. In addition, CS values of other glazing types follow a similar variation: it starts to rise at 08:30 and achieve a plateau from 10:45 to 14:30, and then go down toward late afternoon (16:00). Specifically, mean CS values of clear, grey, blue and red glazing are falling into a range of 0.55-0.62 between 10:45 to 14:30, while the CS range for green and bronze glazing is 0.45~0.55. For most times of the experiment, six glazing systems (excluding darkblue) have brought in a higher CS value (> 0.3), expressing that with them the lighting condition in this room would effectively reduce sleepiness and increase vitality and alertness in participants, similar to the discussions in a field study [30].

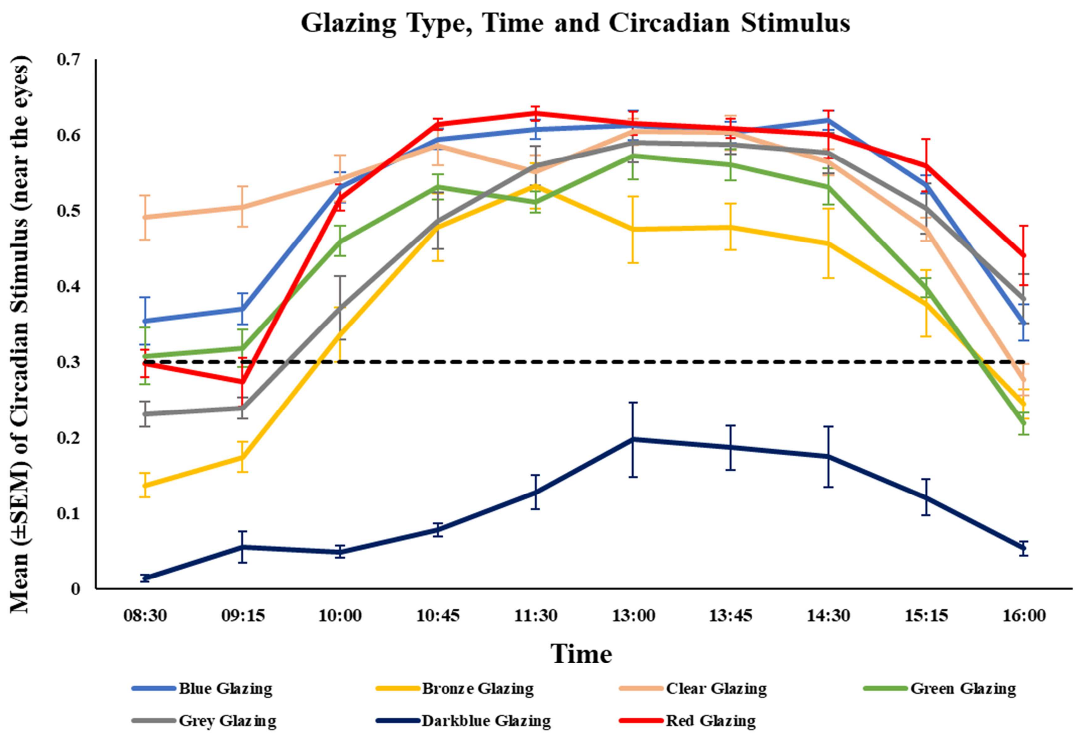

Figure 5. Variations of Circadian Stimulus (CS) of various glazing types and times: mean (±SEM) values (near participants' eyes).

3.3 Effect of glazing colour and time on KSS scores

A two-way ANOVA was conducted to explore how the glazing colour and time affect participants' subjective sleepiness and alertness (Figure 2). Clearly, there are significant main effects of time [F (9, 690) = 8.778, p < 0.001], while no significant main effects could be found for the glazing colour [F (6, 690) = 1.955, p = 0.070]. In Figure 6 and Table 3, pairwise comparisons using the Tukey HSD procedure show significant differences in KSS scores between different times (p < 0.05). KSS scores at 08:30, 09:15, 10:00, 10:45 and 11:30 were significantly higher than those at 13:45, 14:30 and 15:15. This could mean participants tend to feel more alert in the morning and feel sleepy after lunch, which may correspond to the fact that these Chinese participants usually have an afternoon nap between 13:00 and 15:00. No significance can be found for the interaction effect between glazing colour and times [F (54, 690) = 0.598, p = 0.990].

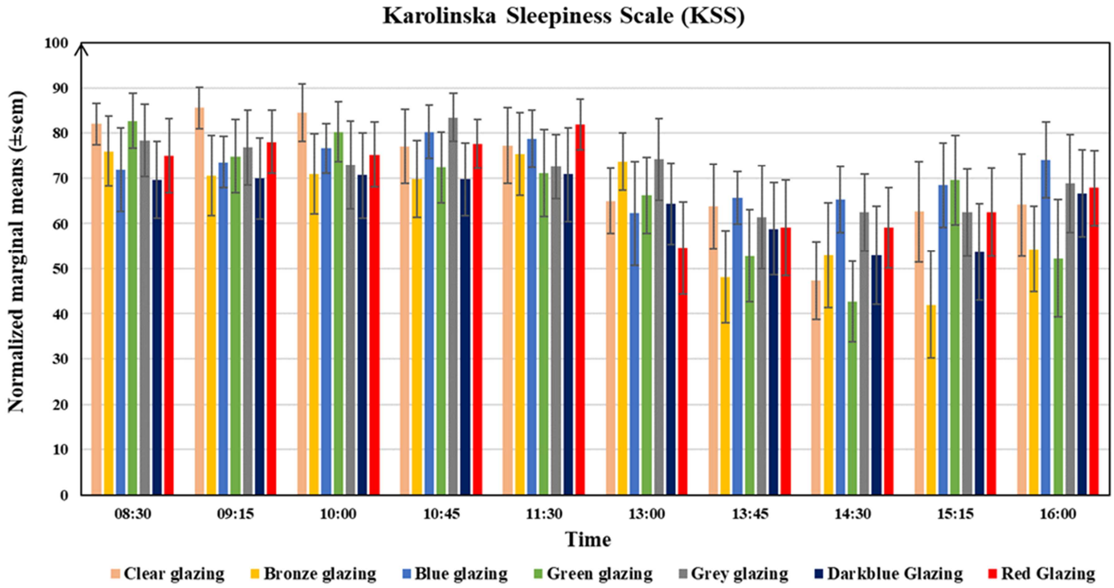

Figure 6. KSS feedback at ten times and with seven glazing types: mean normalized scores; the error bars represent the standard error of the mean (SEM).

3.4 Effect of glazing colour and time on PANAS scores

For the positive mood, the two-way ANOVA revealed significant main effects of glazing colour [F (6, 270) = 4.157, p = 0.001]. However, there was no significant main effects found for the time on the positive mood [F (3, 27) = 1.479, p = 0.221]. Similarly, only the main effects of glazing colour on the negative mood were significant [F (6, 270) = 4.154, p = 0.001], whereas the time will not deliver significant main effects on the mood [F (3, 27) = 0.134, p = 0.940]. No significance can be found in the interaction effects for both positive mood [F 18, 270) = 0.548, p = 0.933] and negative mood [F 18, 270) = 0.511, p = 0.952].

As presented in Figure 7 and Table 4, Post-Hoc (Tukey HSD) analysis demonstrates that the clear glazing has a significantly higher score of positive mood than the darkblue glazing (p < 0.001), green glazing (p = 0.003) and red glazing (p = 0.050). This shows that the clear glazing would help reduce stress and improve mood of participants in this daylit room. Moreover, no significant differences of the main effects on positive mood can be achieved between the clear, bronze and blue glazing (p > 0.05). In contrast, the darkblue glazing delivered a significantly higher score of negative mood than the bronze glazing (p = 0.043), clear glazing (p = 0.009) and grey glazing (p = 0.015), expressing that participants would receive more negative mood with this glazing. Interestingly, even with a lower daylight illuminance than the darkblue glazing, the grey glazing can still affect participants with less stress.

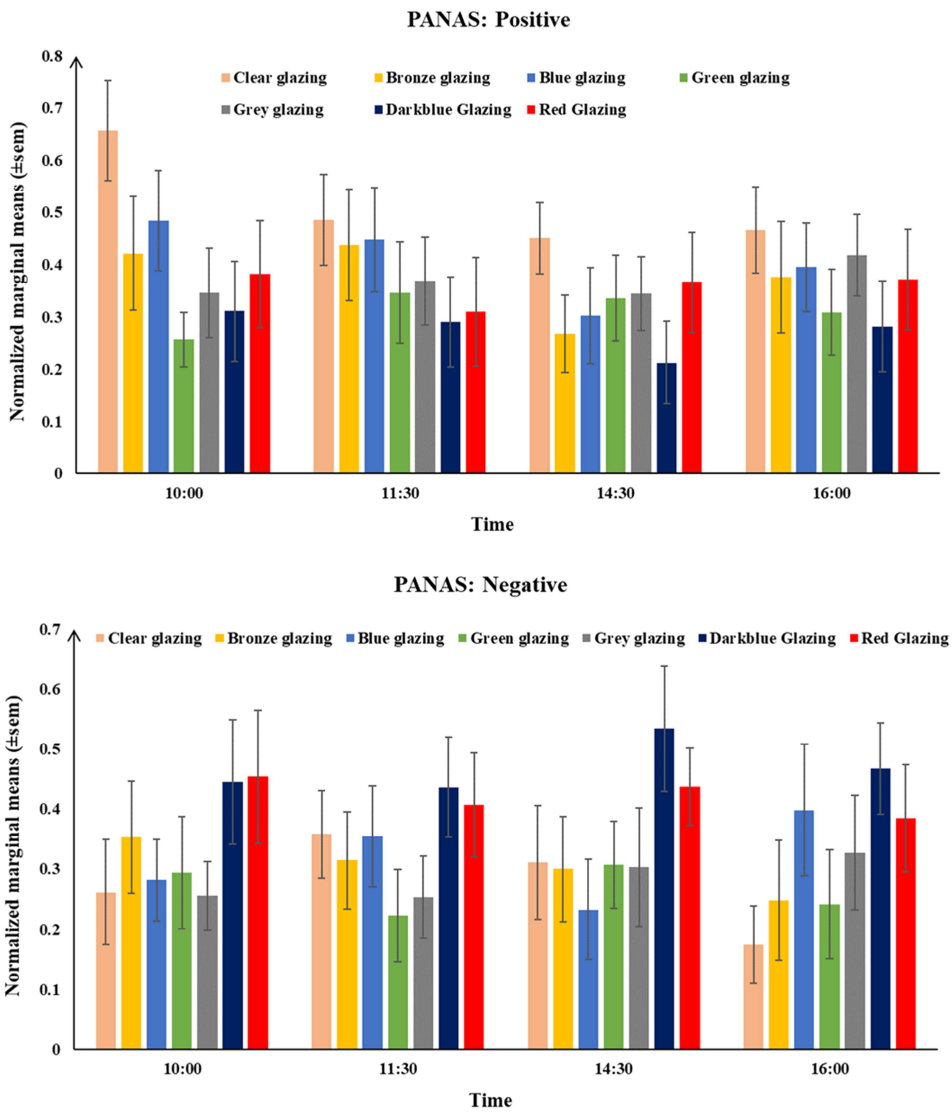

Figure 7. PANAS feedback (positive and negative) at four times and with seven various glazing types: mean normalized scores; the error bars represent the standard error of the mean (SEM).

3.5 Effect of glazing colour and time on work performances

In Figure 8, using the two-way ANOVA analysis, significant main effects of glazing colour were found on two scores of GO/NOGO test, such as RT [$F(6, 270) = 3.435$, $p < 0.001$], and Tput [$F(6, 279) = 8.888$, $p < 0.001$]. Nevertheless, the ANOVA analysis did not support there were significant main effects of the time on RT ($p = 0.995$) and Tput ($p = 0.990$). In addition, there were no significant main effects of glazing type and time on OA (glazing type: p = 0.690; time: p = 0.316). The glazing type × time interaction was not significant for all scores including OA (p = 0.929), RT (p = 0.963), and Tput (p = 0.968).

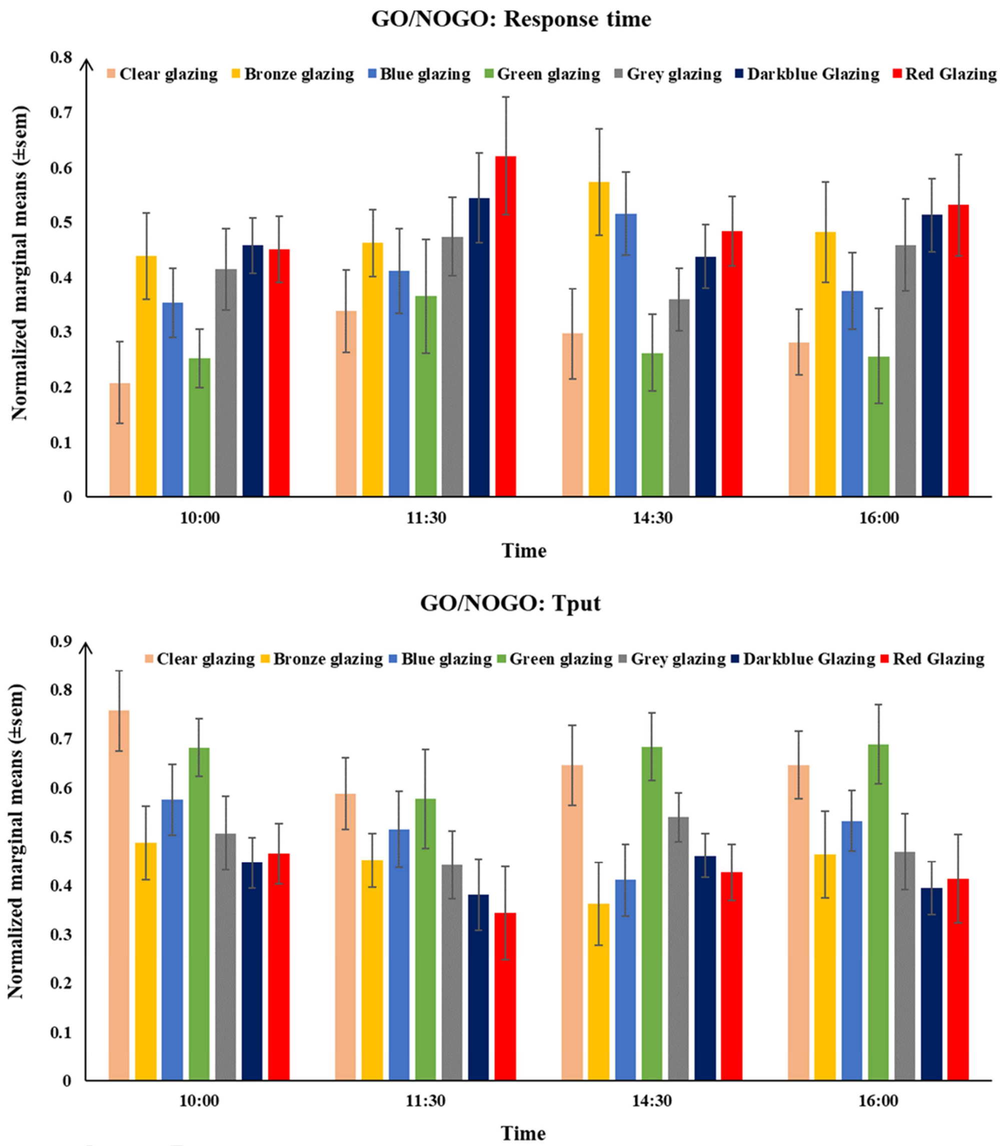

Figure 8. GO/NOGO testing results with seven glazing colours and four times: mean normalized response time and Tput; the error bars represent the standard error of the mean.

Pairwise comparisons (Tukey HSD) given in Table 5 display that the clear glazing has a significantly lower RT in comparison to the bronze glazing (p = 0.001), darkblue glazing (p = 0.001) and red glazing (p < 0.001) glazing, and has a significantly higher Tput score than the blue glazing (p = 0.044), grey glazing (p = 0.014) and red glazing (p < 0.001). These indicate that participants tend to respond to GO/NOGO test more quickly and have a better work performance with the clear glazing. More interestingly, the green glazing gives rise to a significantly lower RT than the bronze glazing ($p = 0.002$) and red glazing ($p < 0.001$), and achieves a significantly higher Tput score than the blue glazing ($p = 0.047$), grey glazing ($p = 0.015$), bronze glazing ($p < 0.001$) and red glazing ($p < 0.001$). Therefore, it seems that the clear and green glazing might be more suitable for improving the working performance in terms of RT and Tput.

3.6 Effect of glazing colour and time on visual performance

In Table 6 and 7, the two-way ANOVA revealed that there were significant main effects of glazing type and time on the feedback of all self-reported visual questions of VQ1-10 ($p < 0.05$). The mean normalized scores and the square error of the mean (SEM) are also displayed in the two tables.

Pairwise comparisons (Tukey HSD) were conducted to test the differences of main effects between glazing types or times (significant differences can be found in Appendix. A and B). With regard to the glazing types [Appendix. A (1-10)], several important results are given as follows: 1) For VQ1-5, VQ8 and VQ10, the blue, clear, bronze glazing can achieve significantly higher scores than the green, darkblue and red glazing ($p < 0.05$). 2) However, for VQ9, scores of the green, darkblue and red glazing are significantly higher than those of the blue, clear and bronze glazing ($p < 0.05$). 3) VQ6 and VQ7 can generally see significantly lower scores for the blue, clear and bronze glazing than the green, darkblue and red glazing ($p < 0.05$). 4) Interestingly, the grey glazing only has significant differences of main effects from the red glazing, including higher scores for VQ1-5, VQ8 and VQ10 ($p < 0.05$), and lower scores for VQ6-7 and VQ9 ($p < 0.05$). Given implications of these questions (section 2.7), these results would express that the four common glazing types with a relatively higher transmittance may receive more acceptances in a daylighting space in terms of visual and colour comfort, pleasantness, attractiveness, visual acuity, and colour naturalness. In addition, significant differences of main effects of time are shown in Appendix. B (1-3). Compared with the morning time at 9:15, scores of self-reported feedback in the late afternoon (16:00) are significantly lower for VQ1, VQ3-5 and VQ8 ($p < 0.05$), and are significantly higher for VQ9 ($p < 0.05$). These could show that participants tend to feel unsatisfied with the darker daylight environment and poor colour appearance in the late afternoon in winter. However, for VQ6-7, the times between 10:00 and 12:00 can see significantly higher scores than the time of 16:00 ($p < 0.05$). A higher daylighting level in the morning would normally deliver a brighter environment. Interestingly, there were no significant differences between 10:00 and 14:30 for most questions ($p > 0.05$).

Furthermore, the glazing type × time interaction was not significant for VQ1-4 and VQ6-10 ($p > 0.05$). However, VQ5 has a significant interaction effect ($p = 0.004$), which would demonstrate that the combined effects of glazing colour and time may significantly affect participants' feedback of whether the light level is sufficient on the table.

4. Discussions and Conclusions

The present experiment of human performance in this article has exposed some findings relating to alertness and sleepiness, mood, working performance, and visual satisfaction of lighting and colour, taking into account various glazing systems (colour / transmittance), working times and daylighting conditions.

First, participants' alertness and self-reported sleepiness in daytime have no significant link to the glazing colour, but can receive significant impact from the time. As discussed in a newly published study [17], no solid proof can be found so far to support that the light colour affects subjective sleepiness. Even though this study has a limitation of using two CCT values (2700 K and 6500 K) [17], it could be possibly considered as one of reasons to explain the human response to glazing colour in this experiment. As mentioned in a review of light effect on alertness [20], the long wavelength irradiance is probably an effective light intervention for increasing alertness levels at night, but is less effective during the daytime. However, a more important explanation could be based on the theory of Circadian Light and Circadian Stimulus [34] (see section 2.2). As shown in Figure 5, a higher Circadian Stimulus level (≥ 0.3 [30]) can be achieved with most glazing systems excluding the darkblue. This would substantially explain why participants' alertness could be kept at a higher level and their sleepiness tended to be reduced when working in this room in daytime. On the other hand, this article found that the varying time would deliver different levels of alertness and sleepiness, in particular between morning and afternoon. The reason for this phenomenon could be beyond the scope of light and colour. According to an investigation into sleep quality [48], daytime napping is a cross-cultural phenomenon and it may influence human alertness and performance. The Chinese participants in this experiment usually have a hobby of afternoon napping, which might give rise to the differences of alertness brought by the time.

Second, it has been found participants' mood in daytime receives significant effects from the glazing colour / type; while the time has no relationship with human mood in this office. A cross-cultural study has pointed out that there is a clear link between colour and mood in indoor work environments [11]. However, it seems that strong colours with higher saturation levels are not desirable [12, 49]. These would explain why the glazing with relatively neutral colour (clear, bronze and blue) could deliver more positive mood than the coloured glazing (green, red, darkblue). In respect to the worst performance of darkblue glazing, three critical factors can be considered as reasons, such as daylight illuminance, visual transmittance and colour saturation. With a strong blue colour and a low visual transmittance of 0.25 (Figure 2), the darkblue glazing has just delivered relatively low daylight illuminances (overall mean: around 500 lux). Consequently, it could not be difficult to understand why participants achieved more negative mood with it. Moreover, it seems that glazing visual transmittance plays a more critical role in improving occupants' satisfaction [24, 25, 50]. Although the grey glazing has lower overall daylight illuminances than the darkblue type, a high transmittance of 0.7 helped the former to achieve more acceptances than the latter. In addition to these explanations, Circadian Light and Circadian Stimulus [34] can be applied for justifying the mood (Figure 5). The darkblue glazing apparently has a very low CS (< 0.3), which could fail to properly regulate participants' circadian systems in daytime. This might bring in a bad mood as mentioned in the study [7]. From 9:15 to 16:00, most of glazing systems can keep a CS range of 0.3~0.7, while another CS range of 0~0.3 is found with the darkblue. The relatively stable CS levels with varying times could explain the insignificant effect of time on mood.

Third, as discussed in section 3.5, the clear and green glazing could achieve better working performances in a reaction time test than other glazing systems, indicated by shorter response time (RT) and higher Tput score. However, given two newly published reviews [19, 20], more evidence is still required to prove how light intensity or spectrum affects the human performance measured in reaction time tasks. At this moment, it could be hard to explain why the clear and green glazing can deliver a better working performance in this experiment.

Forth, participants' visual performances can be significantly affected by the glazing type / colour or time. Based on a study of illuminance, CCT and occupants' satisfaction [51], a proper illuminance level (e.g.

500lux) at workspaces was sufficient to provide a pleasant environment and therefore CCT of light has a negligible effect on ratings of pleasantness. Due to the fact that these findings were achieved with typical light colours (warm white / white / cool white), they could be used to justify that in this experiment, no significant differences of visual satisfaction are found between three common glazing types (clear, blue and bronze) with typical CCT values. Furthermore, it seems that visual transmittance and colour saturation take more effects on self-reported satisfactions than the daylight illuminance. Similar to the discussions above (mood performance), the higher glazing visual transmittance [24, 25] and the lower level of colour saturation [48] make the three glazing types receive more acceptances than the green, darkblue and red glazing. Even though the red glazing delivered much higher illuminance than the grey type, participants tend to choose the latter in the daylit room. The low acceptance of red glazing might be also because that excessive stimulation of red light would make participants feel more stressful [12]. Apparently, effect variations of these visual effects between times well correspond with the varying daylight illuminances in this room.

Given the discussions above, several important findings can be drawn as follows. Circadian Stimulus (CS) could be applied as an indicator of alertness and mood in a daylit workspace with various glazing systems. If a higher CS level (≥ 0.3) can be achieved, glazing colour and transmittance would not take significant effects on alertness and sleepiness. A low CS level (< 0.3) would bring in significant negative mood to occupants. On the other hand, the improvement of occupants' mood would be achieved through increasing glazing visual transmittance and/or decreasing its colour saturation. Self-reported satisfactions show that a preference will be given to the glazing systems with neutral colour and/or higher transmittance in terms of visual performance. It is unknown why the glazing systems with a medium CCT of 4400 K or a higher CCT of 8100 K can deliver shorter response time and better working performance in a reaction time task. It would be necessary to carry on investigations into the human performances and light colour, especially under daylighting conditions.

Limitations: The first limitation of this study could be the number of participants. It would be better if more subjects (e.g. 20 or 30) could be tested. However, one fact would have to be considered: there was a conflict between the seven-day experiment for each participant and the overall number of participants during a limited period (winter). On the other hand, a large number of collected data produced by several testing methods could help produce some useful results. In addition, these conclusions are obviously limited to other issues, such as a specific climate condition (i.e. Beijing region), and specific glazing types and workspace. Parameters relevant to a broader range of participants, architectural settings and daylighting applications will be the subject of future work, including more ages (middle ages, elders, etc.), more room sizes, façade configurations (advanced shading/daylighting devices and glazing systems), indoor lighting systems.

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Tables

Table 1: Mean (±SEM) values of daylight illuminance & CCT near participants' eyes.

	Illuminance and CCT near participants' eyes (Mean ± SEM)										
	Time	**8:30**	**9:15**	**10:00**	**10:45**	**11:30**	**13:00**	**13:45**	**14:30**	**15:15**	**16:00**
Illuminance (lux)	**Blue**	230±45	298±44	635±75	1761±354	2357±630	3714±1248	2645±699	4116±1251	771±193	225±42
	Bronze	66±8	101±18	315±53	1221±311	1887±494	1336±738	1096±303	1348±476	407±69	161±15
	Clear	642±91	699±89	1133±215	2859±779	1488±411	1937±542	4119±1628	1476±345	492±32	157±16
	Darkblue	25±3	47±6	156±22	353±61	719±216	1071±393	1070±201	886±300	603±188	137±18
	Green	172±35	185±28	425±90	692±115	746±187	1747±636	1619±482	919±182	238±15	87±7
	Grey	30±3	45±6	98±20	200±37	445±135	693±234	550±86	569±178	242±63	85±10
	Red	137±11	167±17	778±95	1714±149	3011±794	3170±1382	2594±592	4382±1602	1503±325	448±77
CCT (K)	**Blue**	5780±201	5635±91	5441±49	5704±52	5729±63	5492±98	5568±81	5472±65	5624±88	5831±142
	Bronze	4390±133	4329±74	3795±86	3776±37	3865±77	3777±64	3815±55	3788±60	3881±64	3883±81
	Clear	3978±74	4131±61	4393±52	4456±53	4456±54	4411±67	4433±80	4444±89	4566±110	4997±108
	Darkblue	8698±77	8693±64	8586±42	8685±57	8613±127	8654±97	8656±88	8578±59	8746±101	8736±72
	Green	8219±141	8003±121	8215±56	8317±67	8322±62	8035±102	8144±78	8114±91	8121±83	7990±113
	Grey	4412±90	4184±136	4251±45	4290±89	4306±109	4090±108	4214±131	4133±150	4314±86	4291±109
	Red	1251±20	1284±23	1291±37	1236±36	1254±36	1275±23	1269±32	1246±40	1320±24	1258±26

Table 2: Mean (±SEM) values of daylight illuminance on the table.

	Illuminance on the table (Mean ± SEM)										
	Time	**8:30**	**9:15**	**10:00**	**10:45**	**11:30**	**13:00**	**13:45**	**14:30**	**15:15**	**16:00**
Illuminance (lux)	**Blue**	260±59	286±38	629±48	898±79	2054±417	2502±888	2163±406	1429±344	533±62	218±31
	Bronze	75±7	95±10	426±99	705±137	1316±294	1347±470	1247±239	617±104	362±63	164±14
	Clear	637±51	694±53	919±94	2728±773	4102±940	2280±515	3308±1085	1147±173	505±30	164±10
	Darkblue	19±1	42±4	129±11	232±20	281±39	1959±464	1231±283	787±291	251±35	117±13
	Green	181±35	177±21	307±34	479±57	855±137	1236±304	1289±220	673±157	239±16	93±3
	Grey	31±3	44±7	98±18	185±32	309±55	582±94	539±70	443±125	163±20	81±8
	Red	162±11	178±17	732±58	1525±242	2622±506	3087±1098	3427±747	2712±927	1010±142	455±66

Table 3. Pairwise comparisons of KSS scores between times: Post-Hoc Tukey HSD (Sig. $p < 0.05$).

Pairwise Comparisons: Alertness						
Tukey HSD						
(I) time	**(J) time**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval Lower Bound**	**95% Confidence Interval Upper Bound**
08:30	**13:45**	17.975675	4.0765323	.001	5.036279	30.915071
	14:30	21.832612	4.0765323	.000	8.893216	34.772008
	15:15	16.331684	4.0765323	.003	3.392288	29.271080
09:15	**13:45**	17.074315	4.0765323	.001	4.134918	30.013711
	14:30	20.931251	4.0765323	.000	7.991855	33.870647
	15:15	15.430324	4.0765323	.006	2.490927	28.369720
10:00	**13:45**	17.344362	4.0765323	.001	4.404966	30.283758
	14:30	21.201299	4.0765323	.000	8.261903	34.140695
	15:15	15.700371	4.0765323	.005	2.760975	28.639767
10:45	**13:45**	17.254690	4.0765323	.001	4.315294	30.194086
	14:30	21.111626	4.0765323	.000	8.172230	34.051023
	15:15	15.610699	4.0765323	.005	2.671303	28.550095
11:30	**13:45**	16.865079	4.0765323	.002	3.925683	29.804476
	14:30	20.722016	4.0765323	.000	7.782620	33.661412
	15:15	15.221088	4.0765323	.008	2.281692	28.160485

Table 4. Pairwise comparisons of PANAS (Positive and Negative) between glazing types: Post-Hoc Tukey HSD (Sig. $p < 0.05$).

Pairwise Comparisons: PANAS (Tukey HSD)							
PANAS	**(I) glazing_color**	**(J) glazing_color**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval Lower Bound**	**95% Confidence Interval Upper Bound**
Positive	**Clear**	**Darkblue**	.240724	.0530021	.000	.083270	.398178
		Green	.202524	.0530021	.003	.045070	.359978
		Red	.157429	.0530021	.050	-.000025	.314883
Negative	**Bronze**	**Darkblue**	-.166522	.0550469	.043	-.330051	-.002994
	Clear	**Darkblue**	-.194652	.0550469	.009	-.358181	-.031123
	Darkblue	**Grey**	.185841	.0550469	.015	.022312	.349369

Table 5. Pairwise comparisons of GO/NOGO test (Response time & Tput) between glazing types: Post-Hoc Tukey HSD (Sig. $p < 0.05$).

Pairwise Comparisons: GO/NOGO test (Tukey HSD)							
GO/NOGO	**(I) glazing_color**	**(J) glazing_color**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval Lower Bound**	**95% Confidence Interval Upper Bound**
Response time	**Bronze**	**Clear**	.207812	.0511860	.001	.055753	.359871
		Green	.205204	.0511860	.002	.053145	.357263
	Clear	**Darkblue**	-.206844	.0511860	.001	-.358903	-.054785
		Red	-.240523	.0511860	.000	-.392582	-.088464
	Green	**Red**	-.237915	.0511860	.000	-.389974	-.085857
Tput	**Blue**	**Clear**	-.150863	.0500437	.044	-.299529	-.002198
		Green	-.149811	.0500437	.047	-.298477	-.001146
	Bronze	**Green**	-.216931	.0500437	.000	-.365596	-.068265
	Clear	**Grey**	.169763	.0500437	.014	.021098	.318429
		Red	.246936	.0500437	.000	.098271	.395602
	Green	**Grey**	.168711	.0500437	.015	.020046	.317377
		Red	.245884	.0500437	.000	.097219	.394550

Table 6. The significant main effects of glazing type on ten visual questions: ANOVA (Sig. p < 0.05).

		Mean & SEM								ANOVA Results		
Questions		**Total**	**Clear**	**Blue**	**Bronze**	**Grey**	**Dark blue**	**Green**	**Red**	**N**	**F**	**Sig.**
Q1	**Mean**	54.79	70	76.91	71.13	71.67	37.81	42.25	13.77	770	146.138	0.000
	SEM	1.14	2.53	2.06	1.71	2.21	2.66	2.46	1.37			
Q2	**Mean**	55.16	71.53	76.99	70.03	72.71	35.96	42.92	15.95	770	136.167	0.000
	SEM	1.16	2.44	2.14	1.93	2.27	2.78	2.57	1.45			
Q3	**Mean**	53.79	68.99	76.99	71.79	73.15	31.34	40.62	13.65	770	158.671	0.000
	SEM	1.18	2.3	2.16	1.91	2.21	2.64	2.45	1.55			
Q4	**Mean**	51.6	67.81	73.32	66.32	70.22	31.06	39.48	13.02	770	132.255	0.000
	SEM	1.16	2.51	2.16	2.04	2.29	2.66	2.52	1.31			
Q5	**Mean**	57.46	75.53	77.34	63.32	74.06	37.92	46.78	27.24	770	105.381	0.000
	SEM	1.14	2.07	2.01	2.47	2.25	3.06	2.58	2.54			
Q6	**Mean**	32.1	27	25.29	21.75	23.61	42.97	37.64	46.43	770	13.317	0.000
	SEM	1.21	3.02	2.97	2.58	2.79	3.39	3.16	3.57			
Q7	**Mean**	39.56	32.79	37.09	35.15	33.88	46.71	42.3	49.01	770	7.176	0.000
	SEM	1.03	2.98	3.2	2.53	2.94	2.29	2.46	2.06			
Q8	**Mean**	54.54	77.69	84.28	74.94	82.53	22.26	29.33	10.75	770	329.958	0.000
	SEM	1.29	2.19	1.77	2	1.54	2.13	2.35	1.2			
Q9	**Mean**	38.77	23.86	23.51	29.23	18.73	62.04	47.23	66.77	770	70.237	0.000
	SEM	1.18	2.77	2.6	2.42	1.94	3.05	2.89	2.46			
Q10	**Mean**	53.21	74.57	77.57	71.27	76.65	25.59	35.85	11.03	770	189.575	0.000
	SEM	1.26	2.39	2.41	2.23	2.13	2.44	2.51	1.16			

Table 7. The significant main effects of time on ten visual questions: ANOVA (Sig. p < 0.05).

		Mean & SEM											ANOVA Results		
Questions		**Total**	**8:30**	**9:15**	**10:00**	**10:45**	**11:30**	**13:00**	**13:45**	**14:30**	**15:15**	**16:00**	**N**	**F**	**Sig.**
Q1	**Mean**	54.79	53.91	60.78	58.62	52.88	54.94	52.31	49.65	58.54	57.65	48.63	770	2.963	0.002
	SEM	1.14	3.66	3.74	3.54	3.58	3.45	3.7	3.9	3.4	3.62	3.51			
Q2	**Mean**	55.16	54.01	59.96	58.27	52.93	54.24	51.05	50.38	59.6	59.81	51.31	770	2.589	0.006
	SEM	1.16	3.79	3.79	3.71	3.55	3.4	3.78	3.96	3.5	3.66	3.47			
Q3	**Mean**	53.79	51.28	59.3	56.64	51.76	53.13	52.19	50.81	57.03	58.46	47.3	770	2.666	0.005
	SEM	1.18	3.56	3.86	3.69	3.71	3.6	3.9	3.93	3.63	3.76	3.49			
Q4	**Mean**	51.6	51.47	57.98	54.65	48.97	49.33	47.94	48.81	55.65	54.32	46.9	770	2.375	0.012
	SEM	1.16	3.79	3.88	3.57	3.57	3.59	3.8	3.99	3.47	3.59	3.33			
Q5	**Mean**	57.46	39.87	55.15	61.4	65.32	69.86	71.86	70.99	62.56	46.06	31.48	770	35.606	0.000
	SEM	1.14	3.81	3.75	3.34	3.37	3.16	3.14	3.24	3.11	3.15	2.76			
Q6	**Mean**	32.1	20.33	22.68	34.32	42.74	45.46	46.65	46.66	28.52	18.24	15.4	770	13.317	0.000
	SEM	1.21	3.47	3.45	3.54	3.98	3.6	3.93	4.41	3.41	2.95	2.93			
Q7	**Mean**	39.56	31.48	30.06	38.85	51.47	46.64	50.45	50.69	37.94	29.35	28.7	770	10.854	0.000
	SEM	1.03	2.71	2.68	3.13	3.54	3.18	3.51	3.88	3.13	2.58	2.21			
Q8	**Mean**	54.54	52.21	61.01	55.67	53.23	52.63	53.73	54.2	58.95	56.45	47.33	770	3.217	0.001
	SEM	1.29	4.47	4.31	4.12	4.14	4.11	3.88	4.07	3.96	3.94	3.93			
Q9	**Mean**	38.77	42.42	34.13	34.11	39.25	35.96	36.68	37.81	35.65	40.56	51.1	770	3.283	0.001
	SEM	1.18	3.95	3.7	3.72	3.88	3.86	3.74	3.78	3.48	3.51	3.61			
Q10	**Mean**	53.21	54.3	58.34	54.68	50.09	49.57	52.73	52.29	57.32	54.99	47.86	770	1.899	0.049
	SEM	1.26	4.24	4.13	4.03	3.91	3.84	3.91	3.98	3.98	3.97	3.9			

Appendix. A: Pairwise comparisons of visual performances between glazing types: Post-Hoc, Tukey HSD (Sig. $p < 0.05$).

A (1): VQ1

Question	(I) glazing_color	(J) glazing_color	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Q1	blue	darkblue	39.10078	2.785254	0.000	30.86461	47.33695
		green	34.66784	2.785254	0.000	26.43168	42.90401
		red	63.14582	2.785254	0.000	54.90966	71.38199
	bronze	darkblue	33.31819	2.785254	0.000	25.08203	41.55436
		green	28.88526	2.785254	0.000	20.64909	37.12142
		red	57.36323	2.785254	0.000	49.12707	65.5994
	clear	darkblue	32.18137	2.785254	0.000	23.94521	40.41754
		green	27.74844	2.785254	0.000	19.51227	35.9846
		red	56.22641	2.785254	0.000	47.99025	64.46258
	darkblue	grey	-33.8595	2.785254	0.000	-42.0957	-25.6233
		red	24.04504	2.785254	0.000	15.80888	32.28121
	green	grey	-29.4266	2.785254	0.000	-37.6627	-21.1904
		red	28.47798	2.785254	0.000	20.24181	36.71415
	grey	red	57.90455	2.785254	0.000	49.66839	66.14072

A (2): VQ2

Pairwise Comparisons							
Question	(I) glazing_color	(J) glazing_color	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Q2	blue	darkblue	41.03135	2.854874	0.000	32.58931	49.47339
		green	34.07098	2.854874	0.000	25.62894	42.51301
		red	61.03665	2.854874	0.000	52.59461	69.47869
	bronze	darkblue	34.07516	2.854874	0.000	25.63312	42.51719
		green	27.11478	2.854874	0.000	18.67275	35.55682
		red	54.08046	2.854874	0.000	45.63842	62.52249
	clear	darkblue	35.5681	2.854874	0.000	27.12606	44.01014
		green	28.60773	2.854874	0.000	20.16569	37.04977
		red	55.5734	2.854874	0.000	47.13136	64.01544
	darkblue	grey	-36.7532	2.854874	0.000	-45.1953	-28.3112
		red	20.0053	2.854874	0.000	11.56326	28.44734
	green	grey	-29.7929	2.854874	0.000	-38.2349	-21.3508
		red	26.96567	2.854874	0.000	18.52364	35.40771
	grey	red	56.75853	2.854874	0.000	48.31649	65.20057

A (3): VQ3

Pairwise Comparisons							
Question	**(I) glazing_color**	**(J) glazing_color**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
						Lower Bound	**Upper Bound**
Q3	blue	darkblue	45.65192	2.809233	0.000	37.34485	53.959
		green	36.36911	2.809233	0.000	28.06203	44.67618
		red	63.34084	2.809233	0.000	55.03377	71.64792
	bronze	darkblue	40.45008	2.809233	0.000	32.143	48.75715
		green	31.16726	2.809233	0.000	22.86018	39.47433
		red	58.139	2.809233	0.000	49.83192	66.44607
	clear	darkblue	37.64647	2.809233	0.000	29.33939	45.95354
		green	28.36365	2.809233	0.000	20.05658	36.67073
		red	55.33539	2.809233	0.000	47.02831	63.64246
	darkblue	green	-9.28282	2.809233	0.017	-17.5899	-0.97574
		grey	-41.8104	2.809233	0.000	-50.1175	-33.5033
		red	17.68892	2.809233	0.000	9.381844	25.996
	green	grey	-32.5276	2.809233	0.000	-40.8346	-24.2205
		red	26.97174	2.809233	0.000	18.66466	35.27881
	grey	red	59.4993	2.809233	0.000	51.19223	67.80638

A (4): VQ4

Pairwise Comparisons							
Question	**(I) glazing_color**	**(J) glazing_color**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
						Lower Bound	**Upper Bound**
Q4	blue	darkblue	42.26028	2.907946	0.000	33.66131	50.85926
		green	33.83427	2.907946	0.000	25.2353	42.43325
		red	60.29711	2.907946	0.000	51.69813	68.89608
	bronze	darkblue	35.26488	2.907946	0.000	26.6659	43.86385
		green	26.83887	2.907946	0.000	18.23989	35.43784
		red	53.3017	2.907946	0.000	44.70272	61.90068
	clear	darkblue	36.75544	2.907946	0.000	28.15647	45.35442
		green	28.32943	2.907946	0.000	19.73046	36.92841
		red	54.79227	2.907946	0.000	46.19329	63.39124
	darkblue	grey	-39.1613	2.907946	0.000	-47.7603	-30.5623
		red	18.03682	2.907946	0.000	9.437848	26.6358
	green	grey	-30.7353	2.907946	0.000	-39.3343	-22.1363
		red	26.46283	2.907946	0.000	17.86386	35.06181
	grey	red	57.19814	2.907946	0.000	48.59916	65.79711

A (5): VQ5

Pairwise Comparisons							
Question	**(I) glazing_color**	**(J) glazing_color**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
						Lower Bound	**Upper Bound**
``Q5	blue	bronze	14.01945	2.778404	0.000	5.803533	22.23536
		darkblue	39.41239	2.778404	0.000	31.19648	47.62831
		green	30.55945	2.778404	0.000	22.34354	38.77536
		red	50.09764	2.778404	0.000	41.88173	58.31355
	bronze	clear	-12.2137	2.778404	0.000	-20.4296	-3.99779
		darkblue	25.39295	2.778404	0.000	17.17703	33.60886
		green	16.54	2.778404	0.000	8.324092	24.75592
		grey	-10.7396	2.778404	0.002	-18.9555	-2.52367
		red	36.07819	2.778404	0.000	27.86228	44.2941
	clear	darkblue	37.60665	2.778404	0.000	29.39073	45.82256
		green	28.75371	2.778404	0.000	20.53779	36.96962
		red	48.29189	2.778404	0.000	40.07598	56.5078
	darkblue	green	-8.85294	2.778404	0.025	-17.0689	-0.63703
		grey	-36.1325	2.778404	0.000	-44.3484	-27.9166
		red	10.68525	2.778404	0.003	2.469332	18.90116
	green	grey	-27.2796	2.778404	0.000	-35.4955	-19.0637
		red	19.53819	2.778404	0.000	11.32227	27.7541
	grey	red	46.81777	2.778404	0.000	38.60186	55.03368

A (6): VQ6

Pairwise Comparisons							
Question	**(I) glazing_color**	**(J) glazing_color**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
						Lower Bound	**Upper Bound**
Q6	blue	darkblue	-17.6832	3.89374	0.000	-29.1973	-6.16921
		green	-12.3558	3.89374	0.026	-23.8698	-0.84174
		red	-21.1414	3.89374	0.000	-32.6554	-9.62738
	bronze	darkblue	-21.2158	3.89374	0.000	-32.7299	-9.70179
		green	-15.8884	3.89374	0.001	-27.4024	-4.37432
		red	-24.674	3.89374	0.000	-36.188	-13.16
	clear	darkblue	-15.9679	3.89374	0.001	-27.482	-4.45392
		red	-19.4261	3.89374	0.000	-30.9401	-7.91208
	darkblue	grey	19.36106	3.89374	0.000	7.847029	30.87508
	green	grey	14.03358	3.89374	0.006	2.519556	25.54761
	grey	red	-22.8192	3.89374	0.000	-34.3333	-11.3052

A (7): VQ7

Pairwise Comparisons							
Question	(I) glazing_color	(J) glazing_color	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Q7	blue	red	-11.9187	3.41841	0.009	-22.0271	-1.81025
	bronze	darkblue	-11.5624	3.41841	0.013	-21.6708	-1.45394
		red	-13.8572	3.41841	0.001	-23.9657	-3.74878
	clear	darkblue	-13.9242	3.41841	0.001	-24.0326	-3.81571
		red	-16.219	3.41841	0.000	-26.3274	-6.11055
	darkblue	grey	12.82918	3.41841	0.004	2.720729	22.93763
	grey	red	-15.124	3.41841	0.000	-25.2325	-5.01557

A (8): VQ8

Pairwise Comparisons							
Question	(I) glazing_color	(J) glazing_color	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Q8	blue	darkblue	62.01798	2.505729	0.000	54.60839	69.42758
		green	54.94407	2.505729	0.000	47.53448	62.35367
		red	73.52925	2.505729	0.000	66.11966	80.93885
	bronze	darkblue	52.68022	2.505729	0.000	45.27062	60.08981
		green	45.60631	2.505729	0.000	38.19671	53.0159
		grey	-7.59387	2.505729	0.040	-15.0035	-0.18427
		red	64.19148	2.505729	0.000	56.78189	71.60108
	clear	darkblue	55.42938	2.505729	0.000	48.01978	62.83897
		green	48.35546	2.505729	0.000	40.94587	55.76506
		red	66.94064	2.505729	0.000	59.53105	74.35024
	darkblue	grey	-60.2741	2.505729	0.000	-67.6837	-52.8645
		red	11.51127	2.505729	0.000	4.101673	18.92086
	green	grey	-53.2002	2.505729	0.000	-60.6098	-45.7906
		red	18.58518	2.505729	0.000	11.17558	25.99477
	grey	red	71.78535	2.505729	0.000	64.37575	79.19495

A (9): VQ9

Pairwise Comparisons							
Question	**(I) glazing_color**	**(J) glazing_color**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
						Lower Bound	**Upper Bound**
Q9	blue	darkblue	-38.5278	3.335592	0.000	-48.3913	-28.6642
		green	-23.7147	3.335592	0.000	-33.5782	-13.8511
		red	-43.2542	3.335592	0.000	-53.1178	-33.3907
	bronze	darkblue	-32.8052	3.335592	0.000	-42.6688	-22.9417
		green	-17.9921	3.335592	0.000	-27.8557	-8.12857
		grey	10.50584	3.335592	0.028	0.642287	20.36939
		red	-37.5317	3.335592	0.000	-47.3952	-27.6681
	clear	darkblue	-38.1769	3.335592	0.000	-48.0404	-28.3133
		green	-23.3637	3.335592	0.000	-33.2273	-13.5002
		red	-42.9033	3.335592	0.000	-52.7669	-33.0398
	darkblue	green	14.81313	3.335592	0.000	4.949575	24.67668
		grey	43.31108	3.335592	0.000	33.44753	53.17463
	green	grey	28.49795	3.335592	0.000	18.6344	38.3615
		red	-19.5396	3.335592	0.000	-29.4031	-9.67602
	grey	red	-48.0375	3.335592	0.000	-57.9011	-38.174

A (10): VQ10

Pairwise Comparisons							
Question	(I) glazing_color	(J) glazing_color	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Q10	blue	darkblue	51.97477	2.895573	0.000	43.41238	60.53716
		green	41.71893	2.895573	0.000	33.15654	50.28132
		red	66.53488	2.895573	0.000	57.97249	75.09726
	bronze	darkblue	45.68188	2.895573	0.000	37.11949	54.24426
		green	35.42604	2.895573	0.000	26.86365	43.98842
		red	60.24198	2.895573	0.000	51.6796	68.80437
	clear	darkblue	48.97912	2.895573	0.000	40.41674	57.54151
		green	38.72329	2.895573	0.000	30.1609	47.28567
		red	63.53923	2.895573	0.000	54.97684	72.10162
	darkblue	green	-10.2558	2.895573	0.008	-18.8182	-1.69345
		grey	-51.0561	2.895573	0.000	-59.6185	-42.4937
		red	14.56011	2.895573	0.000	5.997721	23.1225
	green	grey	-40.8003	2.895573	0.000	-49.3627	-32.2379
		red	24.81595	2.895573	0.000	16.25356	33.37833
	grey	red	65.61622	2.895573	0.000	57.05383	74.1786

Appendix (B): Pairwise comparisons of visual performances between times: Post-Hoc, Tukey HSD (Sig. $p < 0.05$).

B (1): VQ1, 2-5

Pairwise Comparisons							
Questions	**(I) time**	**(J) time**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
						Lower Bound	**Upper Bound**
Q1	**9:15**	**16:00**	12.15476	3.329015	0.010	1.588074	22.72145
Q3	**9:15**	**16:00**	12.00169	3.357676	0.014	1.344033	22.65936
	15:15	**16:00**	11.16616	3.357676	0.031	0.508501	21.82382
Q4	**9:15**	**16:00**	11.07475	3.47566	0.048	0.042591	22.10691
Q5	**8:30**	**9:15**	-15.288	3.320828	0.000	-25.8287	-4.74727
		10:00	-21.5324	3.320828	0.000	-32.0731	-10.9917
		10:45	-25.4545	3.320828	0.000	-35.9952	-14.9138
		11:30	-29.9899	3.320828	0.000	-40.5306	-19.4492
		13:00	-31.9937	3.320828	0.000	-42.5345	-21.453
		13:45	-31.1207	3.320828	0.000	-41.6614	-20.58
		14:30	-22.6976	3.320828	0.000	-33.2383	-12.1569
		9:15	-15.288	3.320828	0.000	-25.8287	-4.74727
	9:15	**11:30**	-14.7019	3.320828	0.000	-25.2426	-4.16121
		13:00	-16.7058	3.320828	0.000	-27.2465	-6.16507
		13:45	-15.8328	3.320828	0.000	-26.3735	-5.29207
		16:00	23.67135	3.320828	0.000	13.13065	34.21205
	10:00	**15:15**	15.33879	3.320828	0.000	4.798085	25.87949
		16:00	29.91579	3.320828	0.000	19.37509	40.45649
	10:45	**15:15**	19.26087	3.320828	0.000	8.720169	29.80157
		16:00	33.83787	3.320828	0.000	23.29717	44.37857
	11:30	**15:15**	23.79626	3.320828	0.000	13.25556	34.33696
		16:00	38.37326	3.320828	0.000	27.83256	48.91396
	13:00	**15:15**	25.80012	3.320828	0.000	15.25942	36.34082
		16:00	40.37712	3.320828	0.000	29.83642	50.91782
	13:45	**15:15**	24.92712	3.320828	0.000	14.38641	35.46782
		16:00	39.50412	3.320828	0.000	28.96341	50.04482
	14:30	**15:15**	16.50401	3.320828	0.000	5.963311	27.04472
		16:00	31.08101	3.320828	0.000	20.54031	41.62172
	15:15	**16:00**	14.577	3.320828	0.001	4.036298	25.1177

B (2): VQ6

Pairwise Comparisons							
Question	**(I) time**	**(J) time**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
						Lower Bound	**Upper Bound**
Q6	**8:30**	**10:45**	-22.4068	4.653909	0.000	-37.1788	-7.63471
		11:30	-25.1243	4.653909	0.000	-39.8964	-10.3523
		13:00	-26.3141	4.653909	0.000	-41.0862	-11.5421
		13:45	-26.3301	4.653909	0.000	-41.1021	-11.558
	9:15	**10:45**	-20.0563	4.653909	0.001	-34.8283	-5.28422
		11:30	-22.7738	4.653909	0.000	-37.5459	-8.00177
		13:00	-23.9637	4.653909	0.000	-38.7357	-9.1916
		13:45	-23.9796	4.653909	0.000	-38.7516	-9.2075
	10:00	**15:15**	16.08059	4.653909	0.021	1.308534	30.85265
		16:00	18.91765	4.653909	0.002	4.14559	33.68971
	10:45	**15:15**	24.50267	4.653909	0.000	9.730611	39.27473
		16:00	27.33973	4.653909	0.000	12.56767	42.11178
	11:30	**14:30**	16.94174	4.653909	0.011	2.169682	31.7138
		15:15	27.22022	4.653909	0.000	12.44816	41.99228
		16:00	30.05728	4.653909	0.000	15.28522	44.82934
	13:00	**14:30**	18.13157	4.653909	0.004	3.359508	32.90362
		15:15	28.41005	4.653909	0.000	13.63799	43.18211
		16:00	31.24711	4.653909	0.000	16.47505	46.01916
	13:45	**14:30**	18.14747	4.653909	0.004	3.375416	32.91953
		15:15	28.42596	4.653909	0.000	13.6539	43.19801
		16:00	31.26301	4.653909	0.000	16.49096	46.03507

B (3): VQ7-9

Questions	(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Q7	8:30	10:45	-19.9904	4.085781	0.000	-32.9591	-7.02163
		11:30	-15.1661	4.085781	0.008	-28.1349	-2.19739
		13:00	-18.9691	4.085781	0.000	-31.9379	-6.00039
		13:45	-19.2172	4.085781	0.000	-32.186	-6.24846
	9:15	10:45	-21.4111	4.085781	0.000	-34.3798	-8.44231
		11:30	-16.5868	4.085781	0.002	-29.5556	-3.61807
		13:00	-20.3898	4.085781	0.000	-33.3586	-7.42108
		13:45	-20.6379	4.085781	0.000	-33.6066	-7.66914
	10:45	14:30	13.5273	4.085781	0.033	0.558551	26.49606
		15:15	22.11604	4.085781	0.000	9.147289	35.0848
		16:00	22.76566	4.085781	0.000	9.796901	35.73441
	11:30	15:15	17.2918	4.085781	0.001	4.323049	30.26056
		16:00	17.94142	4.085781	0.001	4.972661	30.91017
	13:00	15:15	21.09481	4.085781	0.000	8.126056	34.06356
		16:00	21.74442	4.085781	0.000	8.775668	34.71318
	13:45	15:15	21.34287	4.085781	0.000	8.374119	34.31163
		16:00	21.99249	4.085781	0.000	9.023731	34.96124
Q8	9:15	16:00	13.68288	2.994919	0.000	4.176653	23.18911
Q9	9:15	16:00	-16.9625	3.986794	0.001	-29.617	-4.30793
	10:00	16:00	-16.9857	3.986794	0.001	-29.6402	-4.3311
	11:30	16:00	-15.1362	3.986794	0.006	-27.7907	-2.48163
	13:00	16:00	-14.4151	3.986794	0.012	-27.0697	-1.76056
	13:45	16:00	-13.2877	3.986794	0.031	-25.9422	-0.6331
	14:30	16:00	-15.4483	3.986794	0.005	-28.1029	-2.79378

Highlights

•Investigation of human performances in a daylit workspace in Beijing, China;

•Impact of glazing colour and transmittance on alertness, mood, working and visual performances;

•Experiments of 11 Chinese participants with seven glazing types and various daily times;

•Implications of effects of glazing and daylighting in terms of Circadian Rhythm and relevant performances.