Exploring the Effects of Daylight and Glazing Types on Self-reported Satisfactions and Performances: A Pilot Investigation in an Office

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Abstract: This article presents a pilot study of effects of glazing on participants' satisfaction and performance in a full-scale office in Beijing, China. Five glazing systems were tested during a heating season (17th Nov 2016 ~ 11th Jan 2017). Research methods include lighting measurements, subjective assessments, and reaction time test (GO/NOGO). Key findings are given as follows: Daylight illuminances associated with glazing types and times of day play a major role of influencing participants' visual performances, alertness, physical wellbeing, and relaxation. The glazing type and CCT of daylight did not significantly affect visual responses if a proper daylight illuminance can be achieved. Circadian Stimulus (CS) under daylighting varies in times of day and glazing types, which would affect participants' alertness and relaxation. Under varying daylight illuminances, some glazing types that can deliver a higher CCT of light would improve participants' physical comfort and give rise to a longer reaction time.

Keywords: Daylighting, Coloured glazing, Visual responses, Participants' satisfaction, Working performance, Office, Beijing.

1. Introduction

Daylighting is a crucial environmental factor in the workspace, due to its significant effects on workers' productivity, health and well-being, and overall comfort (Veitch et al., 2004; Kittler, 2007; Aries et al., 2015). Studies of the impact of daylighting on occupants' performance have become a focus in office buildings. Based on a survey of ten office buildings in Netherlands, Aries et al. (2010) found that workers' visual comfort and well-being are substantially linked to configurations and installations of the external windows, which are capable of delivering daylighting and view. Borisuit et al. (2014) pointed out that office occupants prefer to work with the occurrence of daylighting in terms of visual comfort, mood and alertness. Surveys in several American offices in both winter and summer periods enhanced the importance of daylight availability and its positive impact on stress, mood and sleep quality of office workers, in particular in cold seasons (Figueiro & Rea, 2016; Figueiro et.al, 2017). As highlighted in a new report (Ticleanu & Littlefair, 2017) and a short commentary (Figueiro, 2013), nevertheless, more proofs achieved from the real workspaces would still be required to effectively justify how daylight regulates non-visual aspects of workers. Given a well-known fact that seasonal affective disorders (SAD) are associated with the lack of light (Rosenthal et al., 1985), the season with a lower daylight availability (e.g. winter) is always a focus in northern China (Han et al., 2000).

Due to the application of coated/tinted glass (with static photometric properties and performances), currently, coloured glazing systems can be broadly found in modern commercial buildings across the world (Jelle et. al, 2012; BSI, 2011). The primary functions of these glazing systems are focused on statically adjusting external solar gains, and therefore reducing excessive solar gain to affect the indoor thermal and visual performances (Anderson & Luther, 2012; Jelle et. al, 2012). However, the effect of such coated/tinted glazing systems on visual/colour perceptions and human satisfactions could be more critical, which has been noticed over 20 years (Bulow-Hube, 1995). A pilot study using a scale room in Denmark indicated that the neutral coated glazing with a high visual transmittance could receive more acceptances in a cold climate (Dubois et al., 2007). On the other hand, a Norwegian investigation through subjective surveys found that coloured coated glazing products in the current European market can possibly distort the colour appearances of daylight in modern buildings (Matusiak et al, 2012). In addition, another measurement study exposed that it is necessary to find a proper model to justify the colour quality of the daylight transmitted through different window glazing types (Dangol et al., 2017). Based on the subjective assessments, a Canadian study via a scale model showed that there is a preference for daylight filtered through coloured window glazing and that the glazing colour type may have a significant effect on arousal level of office workers (Arsenault et al., 2012). Interestingly, the study (Arsenault et al., 2012) also revealed that the bronze glazing receives more preferences than the blue and clear glazing among 36 Canadian participants. In addition, the link between colour preference and human performance has been investigated in the workspaces with artificial lighting systems. In USA, an interesting finding has been produced through a human experiment as follows: the narrow long-wavelength (red light: 2568K) can apparently increase alertness and working performance during the daytime (Sahin & Figueiro, 2013). Later, one Italian study further proved that the light colour temperature in workplaces does affect occupants' performance (Bellia et al., 2015). Given the discussions above, several research gaps can be achieved: 1) the number of available human experiments is small; 2) the completed investigations have limited climate conditions and human cultural backgrounds (North America and Europe). Thus, it would still be required to conduct more studies in order to fully explain how the broad-wavelength daylight combined with various glazing systems works on human's psychological and biological functions.

In this article, a pilot experiment study was implemented in an office room in Beijing, China. It aimed to use a full-scale space to investigate how the coloured/neutral glazing affects the Chinese occupants' satisfaction (visual comfort, alertness, well-being, etc.) and working performances in winter.

2. Materials and Methods

2.1. Office Room, Study Design, and Participants

In a heating season from 17th November 2016 to 11th January 2017, this study was conducted in an office (Figure 1) at the School of Architecture of Tsinghua University in Beijing (Latitude: 39.9042° N, Longitude: 116.4074° E). With a dimension of 6.2×3.2×3.8 m, the office room has only one window facing south as well as four sitting positions including A1 & A2 (two working places for participants), B (for the person who conducted measurements and controlled the experiment) and T (for the GONOGO test in section 2.4). The reflectances of room surface are 0.3 (floor), 0.88 (wall) and 0.88 (ceiling).

[Figure 1 near here]

Configures and dimensions of the window are given in Figure 1 (b). The window has the dimension of 2.3×2.3m and a two-layer structure. The external layer is composed of single clear glazing and dividers, whilst the internal layer adopts a removable structure with easily installed/dismantled glazing and dividers. Five glazing types were studied such as clear, blue, bronze, green and grey. They are typical products that can be found in current Chinese market and have been widely applied in modern non-domestic buildings. Figure 1(c) gives pictures of the interior appearances of four coloured glazing systems in the room. The spectral transmittance of all glazing (measured by China Academy of Building Research) can be found in Figure 2. Thus, overall visible transmittance (VT) values of them are 0.91 (clear), 0.55 (blue), 0.37 (bronze), 0.68 (green) and 0.22 (grey).

[Figure 2 near here]

Seventeen participants were recruited from the current students at Tsinghua University, with a mean age of 22.68 (±1.80) years. They have no sleep disorders, and other medical and psychiatric diseases. Across each daily experiment, two participants were asked to sit in the room (the sitting positions were given in Figure 1). Each participant was required to attend a five-day experiment, with only one type of glazing that has been randomly chosen and tested in each day. Conducted in a normal working time (8:30 – 16:00), the daily experiment included two separated time-slots: 08:30-11:30 and 13:00-16:00, with a 1.5 hours lunch break in between. In order to keep a basic level of alertness in the early morning, participants were asked to sleep earlier than 23:00 at the night before the testing day. During the experiment, participants were only allowed to carry out regular office work in the room, such as reading, writing, typing, etc. No food and drinks with caffeine or similar ingredients can be taken by them across the testing period.

2.2. Light Measurements and Calculations

Only the impact of daylight was tested in the experiment. No artificial lighting was applied in the room, even if the daylighting level was insufficient to meet the basic requirements. A portable Illuminance Colour Spectral meter (SPIC-200) was used by the experimenter to collect the data of illuminance (lux), spectrum and correlated colour temperature (CCT, K) of light. The measured positions were the horizontal surface of the working table, and the vertical plane near the participant's eyes (with a height of

35(±5.0) cm above the table). The meter readings were recorded every 10 minutes throughout the experiment. When measuring the lighting, in addition, the indoor temperature and humidity were collected every 3 minutes as a reference to thermal conditions in this room (see the table in Appendix).

Using measured light spectrum and illuminances near participants' eyes, Circadian Light (CL_A) and Circadian Stimulus (CS) were calculated according to the spectral sensitivity of human circadian system (Rea and Figueiro, 2016). The values were adopted as indicators of the nocturnal melatonin suppression due to the spectral response of the human circadian system. 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 (Rea et. al, 2012). The equations of CL_A calculation are given as follows (Rea and Figueiro, 2016):

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

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

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

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

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 melanopsin (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; a_{b-y} = 0.7000; a_{rod} = 3.3000.

In addition, CS can be achieved via the transformation of CL_A using the following algorithm (Rea and Figueiro, 2016):

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

CS has a range of [0~0.7]. The '0' means the threshold for circadian system activation whilst the response saturation will be achieved at the '0.7'. CS is directly proportional to nocturnal melatonin suppression after one-hour exposure (0% to 70%) (Brainard et al., 2001; Rea and Figueiro, 2016). In a field study in offices (Figueiro et al., 2018), CS =0.3 has been recognized as the minimum requirement to reduce sleepiness and increase vitality and alertness of workers.

2.3. Subjective Assessment: VAS Questionnaire

Visual Analogue Scale (VAS) is a valid tool used for measuring subjective responses in psychiatric research (Monk, 1989). Two paper-based VAS questionnaires (scale range: 0-100mm) were designed to test the self-reported satisfaction of participants based on visual and non-visual aspects (see Figure 3). The original questionnaires were presented in Chinese to avoid unnecessary confusion among the Chinese participants.

[Figure 3 near here]

In Figure 3, the questionnaire for visual assessment was composed of eight questions: VQ1, Lighting is comfortable? (0mm, very uncomfortable; 100mm, very comfortable); VQ2, Room is bright? (0 mm, extremely bright; 100 mm, OK); VQ3, Room is dark? (0 mm, extremely dark; 100 mm, OK); VQ4, Light is bright for working? (0 mm, extremely bright; 100 mm, OK); VQ5, Light is dark for working? (0 mm, extremely dark; 100 mm, OK); VQ6, Glare? (0 mm, intolerable; 100 mm, none); VQ7, Light colour is comfortable? (0 mm, very uncomfortable; 100 mm, very comfortable); VQ8, Colour appearance is proper? (0 mm, very improper; 100 mm, excellent). These questions have been proved effective in two field surveys of lighting and human performances in offices (Borisuit et al., 2014; Akashi and Boyce, 2006). For the assessment of non-visual aspects (Figure 3), four questions were used as follows: NVQ1, Alertness (0 mm, very sleepy; 100 mm, very alert); NVQ2, Mood (0 mm, very bad; 100 mm, very good); NVQ3, Physical well-being (0 mm, very bad; 100 mm, very good); NVQ4, Relaxation (0 mm, very tense; 100 mm, very relaxed). The applications of these questions were also reported in the study (Borisuit et al., 2014). Also, the feasibility to apply such questions for studying self-reported human performances has been supported by a psychological survey (Ryan and Frederick, 1997). Scales of VQ2-6 were applied to justify the effect levels of lighting condition: '0mm' means the strongest effect while no clear effect can be found at '100mm'. However, another scale system was used by other questions (VQ1, 7-8; NVQ1-4): 0mm and 100mm indicate the very negative effects and the very positive effects of lighting respectively; whilst a neutral effect can be found at 50mm.

Each participant was asked to complete the two questionnaires every 45 minutes across the daily experiment. Thus, a total of 16 questionnaires will be collected in the day.

2.4. Reaction Time Test: GO/NOGO

As highlighted in a review (Souman et al., 2018), the reaction time task could be crucial for investigating the non-visual effects of light. GO/NOGO, a typical task for testing reaction time, was generally used to measure a participant's capacity for sustained attention and response control (Kreutzer et al., 2011). In this study, participants' working performances were tested using a computer GO/NOGO tool produced using E-prime3 (Experimenter's Prime), a professional psychology software package (https://pstnet.com/products/e-prime/). One computer monitor was used to display the visual stimuli.

Based on the approach suggested in a human experiment (Sahin et al., 2014), each GO/NOGO test of this study lasted around 10 minutes and the participants responded to tasks via a computer mouse (sitting position was displayed in Figure 1(a)). During the test, a smiling or frowning face was presented on a black background every 2-10 seconds. Participants were instructed to do the following actions: 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) (Kreutzer et al., 2011). If the participant's response time is above 1 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. The overall accuracy (OA) will be calculated by [(# of valid responses) / (# of total responses)] (Kreutzer et al., 2011). In addition to the standard scores of RT and OA, Tput was suggested as the third score to enhance the measure of human working performance through linking OA and RT (Sahin et al., 2014). Tput was calculated by [100 × (# of valid responses) / (# of total responses) / (median of the response times)]. If an insignificant difference of OA occurs, Tput can be used to effectively justify the performance variation. The higher value of Tput indicates a better working performance. A valid response in the calculation will not include 'Miss', 'False Alarm', and 'incorrect face clicking', whilst the total responses can include all data.

Each participant attended a GO/NOGO test every 90 minutes during the daily experiment.

2.5. Data Analysis

For the questionnaire feedback and performance tests (GO/NOGO), the raw data from each subject were first normalized using the MinMax scaling to rescale the subjective feedback into a range of zero to one (Blattberg et al., 2010). The rescaling calculation was based on the algorithm of '$(X-X_{min}) / (X_{max}-X_{min})$', X is the raw value of each assessment item. The normalization was applied based on two aims: 1) for subjective questionnaires, it can help minimize unwanted effects of individual differences in term of a given dependent variable (Paul-Dauphin et al., 1999; Hasson & Arnetz, 2005); 2) for the GO/NOGO test, the normalization can avoid the confusions brought by the different units used by the OA, RT, and Tput. A 'five glazing types × eight times' repeated measures of variance (ANOVA) with 'participants' as random factors was performed for the feedback of 12 VAS questions and three GO/NOGO scores (OA, RT, and Tput). A *Post hoc* analysis using the Tukey HSD model (Howell, 2010; Ruxton & Beauchamp, 2008) was further conducted to compare the main effects and interactions. The use of Tukey method was due to the large number of groups of each independent variable (>3) (Howell, 2010). All significant main effects and interactions were achieved when $p < 0.05$ in this study. IBM_SPSS(v24) was the statistical package used for all analysis.

3. Results

This section includes statistical analysis of lighting measurements, feedback of visual and non-visual questions, as well as working performances using GO/NOGO.

3.1. Daylight Illuminance, CCT, and Circadian Stimulus

As shown in Table1, the mean values (±SEM) of vertical illuminance, CCT and Circadian Stimulus (CS) near participants' eyes were given in terms of times of day and glazing types (the surface illuminance at the working plane was not reported here).

[Table 1 near here]

Most of the times of day, the grey and green glazing have higher illuminances than other types. Mean values of illuminances are 1454.3(±237.0) lux and 1407.7(±189.2) lux for grey and green glazing respectively. On the other hand, the lowest illuminance (overall mean) can be found with the blue and bronze glazing as follows: 701.1(±101.6) lux and 620.2(±86.3) lux. The daylighting illuminance of clear glazing is in between (overall mean: 1025(±190.57) lux). It can be noticed that a higher visual transmittance of glazing does not necessarily bring in a higher indoor illuminance in this room. Certainly, the external sky conditions are more critical. From around 10:45 to 14:30, all glazing systems see a mean vertical illuminance above 500 lux, whilst a higher illuminance (>1000lux) can be found in the time period of 12:00 -- 14:30. In the late afternoon (15:00—16:00) all the glazing types give rise to a lower illuminance level (<500 lux). In general, the mean illuminance peaks at 10:45 and 13:45 for all glazing.

As for the mean CCT of light near the participants' eyes, there are some differences found in the daily testing period from 9:15 to 16:00. The blue glazing has the highest mean CCT of 5395(±36.0) K, which could result in a relatively cold/blue lighting atmosphere. It is normal that the lowest mean CCT of 3986(±54.8) K occurs with the application of bronze glazing. This value would be considered as 'neutral' or 'white', rather than 'warm'. The use of green, grey and clear glazing systems can lead to mean CCT values between 4000K and 5000K. A light colour in this range tends to be called as 'cold white'. Interestingly, the green and grey glazing systems achieve a very similar CCT value: overall mean 4700k. The clear glazing, nevertheless, has a slightly lower mean CCT of 4444k. Thus, the three glazing might produce a similar light atmosphere in this office room throughout the experiment.

In addition, Table 1 displays mean values of CS near participants' eyes with the varying times of day and glazing types. Compared with the clear and bronze glazing, the grey, green and blue glazing have higher CS values at most times, which indicates a higher nocturnal melatonin suppression rate (Rea & Figueiro, 2016). This result well corresponds with the variation of vertical illuminance, and could be explained by the fact that CS is significantly influenced by overall daylight level apart from the spectral transmittance of the glazing (Rea & Figueiro, 2016). Moreover, the CS of all glazing follows a similar variation: it starts to rise at 09:15 and achieve a plateau from 10:45 to 14:30, and then go down towards 16:00. To be more specific, the mean CS of green, grey and blue glazing could achieve a range of 0.5-0.55 between 10:45 to 14:30, while the CS range for clear and bronze glazing is 0.35~0.4 in this period. From 10:00 to 15:15, all glazing systems will bring in a CS value > 0.3.

3.2. Results of Subjective Assessment and GO/NOGO Test

3.2.1. Summary of the ANOVA Results

Figure 4 shows a summary of two-way ANOVA analysis of eight visual questions, four non-visual questions, and GO/GONO test. The significant / insignificant main effects and interactions can be found for the glazing colour and time of day.

[Figure 4 near here]

3.2.2. Subjective Assessment: Visual Questions

The two-way ANOVA revealed that there were significant main effects of glazing types (colour) or times of day on the visual questions of VQ1-6 and VQ8 ($p<0.05$). The mean normalized scores of these questions are displayed in Figure 5, 6 & 7. However, significant effects of glazing type and time of day on VQ7 (‘colour comfort’) have not been proved by ANOVA, glazing colour ($p = 0.107$) & time of day ($p = 0.258$).

[Figure 5, 6 & 7 near here]

When only considering the main effects of glazing colour, the significance can be found at the questions: VQ1 ‘lighting comfort’ [$F (4, 623) = 2.707$, $p = 0.029$]; VQ2 ‘ambient brightness’ [$F (4, 623) = 7.006$, $p < 0.001$]; VQ3 ‘ambient darkness’ [$F (4, 623) = 13.691$, $p < 0.001$]; VQ4 ‘brightness for working’ [$F (4, 623) = 5.447$, $p < 0.001$]; VQ5 ‘darkness for working’ [$F (4, 623) = 10.648$, $p < 0.001$]; VQ8 ‘colour appearance’ [$F (4, 623) = 5.573$, $p < 0.001$]. VQ6 ‘Glare’ did not receive significant main impact from the glazing colour ($p > 0.05$). Pairwise comparisons between glazing types using Tukey HSD are demonstrated in Table 2 ($p < 0.05$). With the green and grey glazing, participants generally felt brighter at the working area and across the room than having the blue, bronze and clear glazing (VQ2-5; $p < 0.05$). Compared with the bronze glazing, interestingly, the green and grey glazing can bring in a higher acceptance rate in terms of colour appearance (VQ8) ($p < 0.05$). However, there are no significant differences between clear and other coloured glazing for this question ($p > 0.05$).

[Table 2 near here]

For the time of day, significant main effects were achieved at the questions of VQ2-6 and 8: VQ2 [$F (7, 623) = 16.966$, $p < 0.001$]; VQ3 [$F (7, 623) =12.067$, $p < 0.001$]; VQ4 [$F (7, 623) = 14.244$, $p < 0.001$]; VQ5 [$F (7, 623) =10.980$, $p < 0.001$]; VQ6 [$F (7, 623) = 14.763$, $p < 0.001$]; VQ8 [$F (7, 623) = 2.468$, $p = 0.017$]. The analysis of time of day failed to show significant main effects on VQ1 ‘lighting comfort’ ($p > 0.05$). Pairwise comparisons (Tukey HSD) between seven times revealed some results (Table 3 & 4) ($p < 0.05$). For the ambient brightness and darkness (VQ2 & 3), significant differences were found between 9:15 and 13:45 ($p < 0.001$), and between

10:45 and 16:00 ($p < 0.05$), and between 13:45 and 16:00 ($p < 0.001$). Apparently, ambient brightness increased from 09:15 to 13:45, and then decreased towards 16:00. The brightness and darkness at the working plane (VQ4 & 5) were displayed as a similar result as VQ2 & 3. There were significant differences between 09:15 and 13:45/16:00 ($p < 0.001$), and between 10:45 and 16:00 ($p < 0.001$), and 13:45 and 16:00 ($p < 0.001$). For VQ2-5, generally, the late afternoon (16:00) will bring in the darkest space. The mean scores of the glare (VQ6) at 11:30 and 13:45 were significantly lower than the times at 09:15, 14:30, 15:15 and 16:00 ($p < 0.05$). This could express that participants tend to feel uncomfortable with the lighting from 11:30 to 13:45. For the colour appearance (VQ8), there were significant differences between the morning (10:00 or 11:30) and the late afternoon (16:00) ($p < 0.05$). A better colour appearance can be perceived in the morning than in the late afternoon.

[Table 3 & 4 near here]

The glazing type × time of day interaction was not significant for all questions, VQ1 ($p = 0.444$; power: 76.1%), VQ2 ($p = 0.981$; power: 40.8%), VQ3 ($p = 0.99$; power: 39.6%), VQ4 ($p = 0.708$; power: 63.2%), VQ5 ($p = 0.964$; power: 47.5%), VQ6 ($p = 0.979$; power: 43.5%), VQ7 ($p = 0.987$; power: 37.3%), and VQ8 ($p = 1.0$; power: 22%). The power was computed using alpha = 0.05.

3.2.3. Subjective Assessment: Non-visual Questions

Based on the analysis of two-way ANOVA for the non-visual questions, significant main effects of glazing types or times of day can be found on NVQ1, 3 and 4 ($p < 0.05$) (Figure 8), while no significant main impacts were achieved on NVQ2 ‘mood’ from the glazing type ($p = 0.063$) and time of day ($p = 0.166$).

[Figure 8 near here]

The significant effects of glazing colour can be only found on NVQ3 'Physical wellbeing', [F (4, 623) = 3.619, p = 0.006]. In Table 5, pairwise comparisons using Tukey HSD presented the significant differences between the blue and clear glazing (p = 0.012), and between the clear and grey glazing (p = 0.026). More precisely, the clear glazing received significantly lower scores than the blue and grey glazing, which might mean participants physically feel more comfortable when applying the blue and grey glazing in this room. The green glazing might have similar effects as the blue and grey glazing, due to a marginally significant difference to the clear glazing (p = 0.067).

[Table 5 near here]

As regards the time of day, there were significant main effects on NVQ1 'alertness', [F (7, 623) = 2.365, p = 0.022]; and NVQ4 'relaxation', [F (7, 623) = 2.104, p = 0.041]. For the NVQ4, in Table 6, pairwise comparisons (Tukey HSD) between times displayed significant differences between 10:00 and 15:15 (p = 0.015). Participants would feel more relaxed in the afternoon than in the morning.

[Table 6 near here]

No significant glazing type × time of day interaction can be found for all questions, NVQ1 (p = 0.976; power: 39.9%), NVQ2 (p = 0.914; power: 46.6%), NVQ3 (p = 0.905; power: 52.6%), NVQ4 (p = 0.965; power: 40.5%). The power was computed using alpha = 0.05.

3.2.4. GO/NOGO Test

Using the two-way ANOVA analysis, in Figure 9, significant main effects of glazing colour were found on two scores of GO/NOGO test, such as RT [F (4, 304) = 3.435, p = 0.009], and Tput [F (4, 304) = 3.955, p = 0.004]. For the time of day, nevertheless, the ANOVA analysis did not support the significant main effects on RT (p = 0.995) and

Tput ($p = 0.990$). In addition, there were no significant main effects of glazing type and time of day on the OA (glazing type: $p = 0.868$; time: $p = 0.741$).

[Figure 9 near here]

Given Table 7 & 8, pairwise comparisons (Tukey HSD) demonstrated that there were significant differences between the blue and clear glazing for RT ($p = 0.006$) and Tput ($p = 0.003$). It has been demonstrated that compared with the clear glazing, participants tend to respond to GO/NOGO test more slowly with the blue glazing ($p = 0.006$). For the Tput, therefore, the blue glazing received lower Tput scores than the clear glazing ($p < 0.05$), due to a higher RT value. Since a higher Tput value is associated with a better performance (Sahin et al., 2014), the clear glazing might be more useful for working.

[Table 7 & 8 near here]

The glazing type × time of day interaction was not significant for OA ($p = 0.58$; power: 70.2%), RT ($p = 0.997$; power: 69.2%), and Tput ($p = 0.999$; power: 40.2%). The power was computed using alpha = 0.05.

4. Discussions

This human experiment in an office with five glazing systems has exposed some interesting results concerning self-reported satisfaction and reaction time test across a winter period and under the daylighting condition. [Table 9 near here]

It is clear that participants' visual responses were primarily linked to the variations of daylight illuminances in terms of glazing types and times of day. First, different glazing types combined with sky conditions have delivered various daylight illuminances at the working plane and near the eyes (Table 1). A result of correlation analysis between vertical illuminance, CCT and CS, and visual/non-visual questions was given in Table 9. Compared with other glazing, participants can normally feel brighter at the working position and across the room with the grey and green glazing (VQ2-5). Notwithstanding the CCT variations of glazing, the perception of brightness or darkness were mainly decided by the ambient daylight illuminances. These have been proved in a review of CCT, illuminance and occupant satisfaction (Fotios, 2017). The feedback differences of light comfort (VQ1) brought by various glazing types could be also brought by the varying daylight illuminances. As suggested in the review (Fotios, 2017), a proper illuminance level (e.g. 500lux) was sufficient to provide a pleasant environment. In this study, the occurrences of lower daylight illuminance (e.g. with the bronze glazing) may fail to produce an acceptable environment. This could be considered as the explanation of the feedback divergence of colour appearance (VQ8) between the bronze and green/grey glazing. As for the insignificant effects of glazing colour on the colour comfort (VQ7), the relatively small range of glazing CCT (3900 ~ 5300) could be the reason (Table 1 & 9). Fotios (2017) suggested that CCT has a negligible effect on ratings of pleasantness. Even though this finding was achieved via reviewing human responses with artificial lighting, we could not deny that there is a similar human performance under daylighting (Table 9). Second, given effects of times of day, the daylight illuminance clearly varied from 9:15 to 16:00 (Table 1). It is normal that significant differences of feedback of VQ2-5 & 8 can be found between times of day, especially in the morning (09:15) and the late afternoon (16:00). According to the glare feedback (VQ6), therefore, varying illuminances can be used to explain the significant differences (Table 9). An interesting survey concluded that the glare sensation of artificial lighting received clear effects of time of the day (Kent et.al, 2015). This could further explain the variations of glare sensation in times of day, even under daylighting as mentioned in this study.

In this study, participants' alertness, physical wellbeing and relaxation could be tightly connected to Circadian Stimulus (CS) (Figueiro et.al, 2018), which has been proved as directly proportional to the nocturnal melatonin suppression (Rea and Figueiro, 2016). In Figure 4, CS significantly varied in glazing type and time of day. For physical wellbeing (NVQ3), the glazing with the higher CS would reduce sleepiness and increase vitality and energy in participants (e.g. blue and green glazing). The significant effects of time of day were also due to the CS for NVQ1 (alertness) & NVQ4 (relaxation) (Table 9). For example, the morning time (10:00) has an average CS of 0.43 while the value at 15:15 is 0.36. Participants' alertness levels could be higher in the morning, while they might feel more relaxed in the afternoon. The effects of glazing type and time of day on mood have not been found significant (Table 9), even though the impact of light and colour on occupants' mood has been demonstrated over 10 years (Küller et.al, 2006). The higher average daylight illuminances and CS in all glazing types might mitigate the negative emotion of participants.

For the working performance using GO/NOGO test, a higher mean CS of clear glazing would support a higher Tput delivery than the blue glazing. With a higher CCT, the blue glazing will deliver a longer reaction time than the clear glazing. A similar finding has been reported in a human experiment (Kulve et.al, 2018). It is unclear why no differences of these performances can be found between other glazing systems and various times of day.

5. Conclusions

Several findings can be drawn from the discussions above. In a working environment, daylight illuminances associated with various glazing systems and times of day play a major role of affecting participants' visual performances, alertness, physical wellbeing, and relaxation. The glazing types and relevant CCT of daylight would not significantly influence participants' visual responses if a proper daylight illuminance can be achieved. Circadian Stimulus delivered by daylight varies in times of day and glazing types, which would lead to the variations of alertness and relaxation in participants. Some glazing systems (e.g. blue) would possibly improve participants' physical comfort through potentially increasing the Circadian Stimulus of daylight. Under a varying daylighting condition, the reaction time was still proved longer with a higher CCT produced by some glazing types (e.g. blue).

Achieved from a pilot study, these conclusions are obviously limited to a specific climate condition, one office room and several typical glazing types. The methods to collect self-reported satisfaction could be relatively simple. In addition, it could be recognized that the impact of seasonal affective disorders (Rosenthal et al., 1985) has not be fully included in the experiment, which might be linked to some human performances. In the next stage, a larger range of glazing type will be studied using more accurate investigation tools.

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Appendix

[Appendix Table is here.]

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Figure 8: Normalized feedback of NVQ1, NVQ3, and NVQ4 with five glazing systems and various times: Mean (±SEM) values (Sig. $p<0.05$).

Figure 9: Testing results of GO/NOGO with five glazing systems and four times: normalized mean (±SEM) values of response time (RT). (Sig. $p<0.05$).

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

Illuminance, CCT, CS near participants' eyes (Mean ± SEM)									
	Time of Day	**9:15**	**10:00**	**10:45**	**11:30**	**13:45**	**14:30**	**15:15**	**16:00**
Illuminance (lux)	**Clear**	453±125	837±252	1132±344	703±147	3035±1222	1578±590	325±77	132±28
	Blue	229±57	426±93	813±193	832±180	1803±617	1034±296	293±50	151±25
	Bronze	171±35	382±77	735±236	999±326	1285±382	1006±312	251±42	129±21
	Green	619±87	1408±237	1916±425	1217±300	3939±1164	1565±324	438±46	155±15
	Grey	570±105	1137±192	2431±704	1702±466	3699±1495	1475±431	422±72	195±24
CCT (K)	**Clear**	4287±76	4419±51	4380±59	4288±58	4340±62	4469±59	4539±64	4825±97
	Blue	5466±148	5265±125	5290±101	5269±90	5349±77	5440±78	5584±76	5507±79
	Bronze	4076±116	3767±99	3915±103	3883±122	3999±195	3998±195	4003±173	4245±195
	Green	4494±55	4677±76	4785±64	4792±56	4753±76	4819±82	4845±84	5170±103
	Grey	4673±181	4770±150	4828±146	4840±138	4513±155	4697±142	4754±141	4716±153
CS	**Clear**	0.319±0.060	0.371±0.057	0.414±0.053	0.427±0.048	0.422±0.060	0.389±0.061	0.302±0.052	0.215±0.038
	Blue	0.285±0.035	0.398±0.037	0.493±0.027	0.511±0.024	0.520±0.034	0.481±0.032	0.379±0.032	0.266±0.030
	Bronze	0.215±0.031	0.329±0.042	0.393±0.045	0.405±0.046	0.438±0.044	0.399±0.045	0.287±0.036	0.200±0.024
	Green	0.477±0.025	0.556±0.015	0.556±0.024	0.516±0.034	0.556±0.040	0.532±0.036	0.430±0.032	0.272±0.023
	Grey	0.416±0.041	0.501±0.044	0.534±0.042	0.527±0.038	0.528±0.036	0.498±0.035	0.404±0.038	0.306±0.027

Table 2: Pairwise comparisons of feedback of VQ (2-5, 8) between glazing types: Post-Hoc Tukey HSD (Sig. $p < 0.05$).

Pairwise Comparisons (Tukey HSD)							
Questions	**(I) glazing_colour**	**(J) glazing_colour**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
						Lower Bound	**Upper Bound**
VQ2	blue	green	12.1934	3.07874	0.001	3.7707	20.6162
	bronze	green	14.6169	3.07306	0.000	6.2097	23.0241
		grey	8.8521	3.07306	0.033	0.4448	17.2593
VQ3	blue	green	-9.7395	3.28418	0.026	-18.7243	-0.7547
		grey	-14.6800	3.28418	0.000	-23.6648	-5.6952
	bronze	green	-11.5162	3.27811	0.004	-20.4845	-2.5480
		grey	-16.4568	3.27811	0.000	-25.4250	-7.4886
	clear	green	-15.7592	3.27811	0.000	-24.7274	-6.7910
		grey	-20.6997	3.27811	0.000	-29.6679	-11.7315
VQ4	blue	green	9.9541	3.07933	0.011	1.5298	18.3785
	bronze	green	13.1050	3.07364	0.000	4.6962	21.5138
	clear	green	8.5654	3.07364	0.043	0.1566	16.9742
VQ5	blue	grey	-12.8847	3.29177	0.001	-21.8903	-3.8791
	bronze	green	-12.3799	3.28569	0.002	-21.3688	-3.3909
		grey	-16.8098	3.28569	0.000	-25.7988	-7.8209
	clear	green	-12.2273	3.28569	0.002	-21.2162	-3.2384
		grey	-16.6572	3.28569	0.000	-25.6462	-7.6683
VQ8	bronze	green	-13.0137	3.24536	0.001	-21.8923	-4.1351
		grey	-13.4594	3.24536	0.000	-22.3380	-4.5808

Table 3: Pairwise comparisons of feedback of VQ (2-4) between times of day: Post-Hoc Tukey HSD (Sig. $p < 0.05$).

Pairwise Comparisons (Tukey HSD)							
Questions	**(I) time of day**	**(J) time of day**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval Lower Bound**	**95% Confidence Interval Upper Bound**
VQ2	**09:15**	**10:00**	12.4593	3.88714	0.031	0.6375	24.2810
		10:45	17.3069	3.88714	0.000	5.4851	29.1287
		11:30	19.0670	3.88714	0.000	7.2453	30.8888
		13:45	25.6229	3.88714	0.000	13.8011	37.4446
	10:00	**13:45**	13.1636	3.88714	0.017	1.3418	24.9854
		15:15	-15.8865	3.89869	0.001	-27.7434	-4.0296
		16:00	-16.5192	3.88714	0.001	-28.3410	-4.6974
	10:45	**14:30**	-13.5616	3.88714	0.012	-25.3834	-1.7398
		15:15	-20.7341	3.89869	0.000	-32.5910	-8.8772
		16:00	-21.3669	3.88714	0.000	-33.1886	-9.5451
	11:30	**14:30**	-15.3217	3.88714	0.002	-27.1435	-3.4999
		15:15	-22.4942	3.89869	0.000	-34.3512	-10.6373
		16:00	-23.1270	3.88714	0.000	-34.9488	-11.3052
	13:45	**14:30**	-21.8775	3.88714	0.000	-33.6993	-10.0558
		15:15	-29.0501	3.89869	0.000	-40.9070	-17.1932
		16:00	-29.6828	3.88714	0.000	-41.5046	-17.8610
VQ3	**09:15**	**10:45**	-16.7655	4.14652	0.002	-29.3761	-4.1549
		11:30	-17.6544	4.14652	0.001	-30.2650	-5.0438
		13:45	-17.9734	4.14652	0.000	-30.5841	-5.3628
	10:00	**16:00**	23.4912	4.14652	0.000	10.8806	36.1019
	10:45	**16:00**	27.8269	4.14652	0.000	15.2163	40.4376
	11:30	**16:00**	28.7159	4.14652	0.000	16.1052	41.3265
	13:45	**15:15**	12.8660	4.15885	0.043	0.2179	25.5141
		16:00	29.0349	4.14652	0.000	16.4243	41.6455
	14:30	**16:00**	21.3024	4.14652	0.000	8.6918	33.9131
	15:15	**16:00**	16.1689	4.15885	0.003	3.5208	28.8170
VQ4	**09:15**	**10:45**	15.0811	3.88788	0.003	3.2571	26.9051
		11:30	18.4071	3.88788	0.000	6.5831	30.2311
		13:45	22.1409	3.88788	0.000	10.3169	33.9649
	10:00	**13:45**	12.3186	3.88788	0.034	0.4945	24.1426
		15:15	-14.0731	3.89943	0.008	-25.9322	-2.2139
		16:00	-14.3108	3.88788	0.006	-26.1348	-2.4868
	10:45	**15:15**	-19.3318	3.89943	0.000	-31.1910	-7.4727
		16:00	-19.5696	3.88788	0.000	-31.3936	-7.7456
	11:30	**14:30**	-14.7180	3.88788	0.004	-26.5420	-2.8940
		15:15	-22.6578	3.89943	0.000	-34.5170	-10.7987
		16:00	-22.8956	3.88788	0.000	-34.7196	-11.0716
	13:45	**14:30**	-18.4518	3.88788	0.000	-30.2758	-6.6278
		15:15	-26.3916	3.89943	0.000	-38.2508	-14.5325
		16:00	-26.6294	3.88788	0.000	-38.4534	-14.8054

Table 4: Pairwise comparisons of feedback of VQ (5, 6, 8) between times of day: Post-Hoc Tukey HSD (Sig. $p < 0.05$).

Pairwise Comparisons (Tukey HSD)							
Questions	**(I) time of day**	**(J) time of day**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
						Lower Bound	**Upper Bound**
VQ5	**09:15**	**10:45**	-14.1695	4.15610	0.016	-26.8092	-1.5297
		11:30	-15.0990	4.15610	0.007	-27.7388	-2.4593
		16:00	13.5040	4.15610	0.027	0.8642	26.1437
	10:00	**16:00**	23.7061	4.15610	0.000	11.0663	36.3458
	10:45	**15:15**	15.1058	4.16845	0.008	2.4285	27.7831
		16:00	27.6734	4.15610	0.000	15.0337	40.3132
	11:30	**15:15**	16.0354	4.16845	0.003	3.3580	28.7127
		16:00	28.6030	4.15610	0.000	15.9632	41.2427
	13:45	**15:15**	12.9653	4.16845	0.041	0.2880	25.6426
		16:00	25.5329	4.15610	0.000	12.8932	38.1727
	14:30	**16:00**	19.0152	4.15610	0.000	6.3754	31.6549
VQ6	**09:15**	**10:00**	12.6838	3.99621	0.034	0.5303	24.8372
		10:45	18.2029	3.99621	0.000	6.0494	30.3564
		11:30	19.8866	3.99621	0.000	7.7331	32.0400
		13:45	22.5184	3.99621	0.000	10.3649	34.6719
	10:00	**15:15**	-14.9488	4.00809	0.005	-27.1384	-2.7592
		16:00	-17.7484	3.99621	0.000	-29.9019	-5.5949
	10:45	**14:30**	-13.6970	3.99621	0.015	-25.8504	-1.5435
		15:15	-20.4679	4.00809	0.000	-32.6575	-8.2783
		16:00	-23.2675	3.99621	0.000	-35.4210	-11.1140
	11:30	**14:30**	-15.3806	3.99621	0.003	-27.5341	-3.2272
		15:15	-22.1516	4.00809	0.000	-34.3412	-9.9620
		16:00	-24.9512	3.99621	0.000	-37.1047	-12.7977
	13:45	**14:30**	-18.0125	3.99621	0.000	-30.1660	-5.8590
		15:15	-24.7834	4.00809	0.000	-36.9730	-12.5938
		16:00	-27.5830	3.99621	0.000	-39.7365	-15.4295
VQ8	**10:00**	**16:00**	13.0736	4.10509	0.033	0.5889	25.5582
	11:30	**16:00**	14.5450	4.10509	0.010	2.0604	27.0296

Table 5: Pairwise comparisons of feedback of NVQ3 between glazing types: Post-Hoc Tukey HSD (Sig. $p < 0.05$).

Pairwise Comparisons (NVQ3: Tukey HSD)						
(I) glazing_colour	**(J) glazing_colour**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
					Lower Bound	**Upper Bound**
blue	clear	9.9446	3.10390	0.012	1.4530	18.4361
clear	grey	-9.1906	3.09816	0.026	-17.6665	-0.7147

Table 6: Pairwise comparisons of feedback of NVQ4 between times of day: Post-Hoc Tukey HSD (Sig. $p < 0.05$).

Pairwise Comparisons (NVQ4: Tukey HSD)						
(I) time of day	**(J) time of day**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
					Lower Bound	**Upper Bound**
10:00	15:15	-13.2814	3.87689	0.015	-25.0720	-1.4908

Table 7: Pairwise comparisons of GO/NOGO testing (response time) between glazing types: Post-Hoc Tukey HSD (Sig. $p < 0.05$).

Pairwise Comparisons (Response time: Tukey HSD)						
(I) glazing_colour	**(J) glazing_colour**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
					Lower Bound	**Upper Bound**
blue	**clear**	0.171335	0.049788	0.006	0.034707	0.307964

Table 8: Pairwise comparisons of GO/NOGO testing (Tput) between glazing types: Post-Hoc Tukey HSD (Sig. $p < 0.05$).

Pairwise Comparisons (Tput: Tukey HSD)						
(I) glazing_colour	**(J) glazing_colour**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
					Lower Bound	**Upper Bound**
blue	**clear**	-0.181677	0.049933	0.003	-0.318706	-0.044647

Table 9: Correlations (Spearman's rho) between lighting conditions (daylight illuminance, CCT, and CS near participants' eyes) and visual & non-visual performances (* $p < 0.05$).

Correlations (Spearman's rho)													
		VQ1	**VQ2**	**VQ3**	**VQ4**	**VQ5**	**VQ6**	**VQ7**	**VQ8**	**NVQ1**	**NVQ2**	**NVQ3**	**NVQ4**
Illuminance	Correlation Coefficient	0.013	-.479*	.554*	-.486*	.534*	-.474*	0.073	.230*	0.075	-0.037	-0.002	-.104*
	Sig. (2-tailed)	0.732	0.000	0.000	0.000	0.000	0.000	0.057	0.000	0.051	0.332	0.965	0.006
CCT	Correlation Coefficient	0.016	-0.022	0.030	-0.042	0.029	0.031	0.041	0.015	-0.040	0.026	0.017	0.005
	Sig. (2-tailed)	0.677	0.563	0.442	0.279	0.444	0.416	0.285	0.701	0.294	0.497	0.655	0.899
CS	Correlation Coefficient	0.047	-.463*	.561*	-.470*	.537*	-.449*	.100*	.255*	0.074	-0.010	0.019	-.091*
	Sig. (2-tailed)	0.224	0.000	0.000	0.000	0.000	0.000	0.009	0.000	0.050	0.800	0.617	0.017

Appendix: Table of mean (±SEM) values of indoor air temperature and relative humidity during the experiment.

Air Temperature and Relative Humidity (Mean ± SEM)									
	Time of Day	**9:15**	**10:00**	**10:45**	**11:30**	**13:45**	**14:30**	**15:15**	**16:00**
Air Temperature (°C)	**Clear**	22.7±0.3	23.2±0.2	23.9±0.3	25.3±0.3	26.6±0.9	24.3±0.2	24.2±0.3	23.6±0.1
	Blue	21.5±0.1	22.3±0.1	22.9±0.1	24.4±0.3	25.3±0.5	24.1±0.2	23.9±0.2	23.6±0.2
	Bronze	21.4±0.2	22.3±0.3	22.8±0.3	24.3±0.4	25.8±0.6	24.2±0.4	23.8±0.4	23.2±0.3
	Green	22.8±0.1	23.8±0.1	24.8±0.1	27.3±0.6	28.1±0.7	25.7±0.3	25.3±0.2	24.8±0.2
	Grey	22.8±0.2	23.8±0.2	24.6±0.2	25.8±0.4	25.7±0.5	24.9±0.3	25.0±0.3	24.5±0.2
Relative Humidity (%)	**Clear**	27.1±1.5	26.9±1.5	25.8±1.3	24.4±1.5	22.6±2.0	24.0±1.7	23.7±1.6	24.5±1.7
	Blue	24.9±0.7	24.9±0.7	24.3±0.7	23.1±0.8	22.1±0.9	23.9±0.7	24.2±0.7	25.0±0.7
	Bronze	24.6±0.9	24.3±0.9	23.9±0.9	22.9±1.1	21.1±1.2	23.0±1.0	23.4±1.1	24.4±1.0
	Green	25.0±0.6	25.2±0.6	24.5±0.6	22.3±0.8	20.4±1.0	23.4±0.7	23.9±0.7	24.2±0.6
	Grey	22.6±0.7	22.6±0.6	21.6±0.5	20.5±0.6	19.3±0.7	20.8±0.5	21.2±0.5	22.0±0.5

Figures

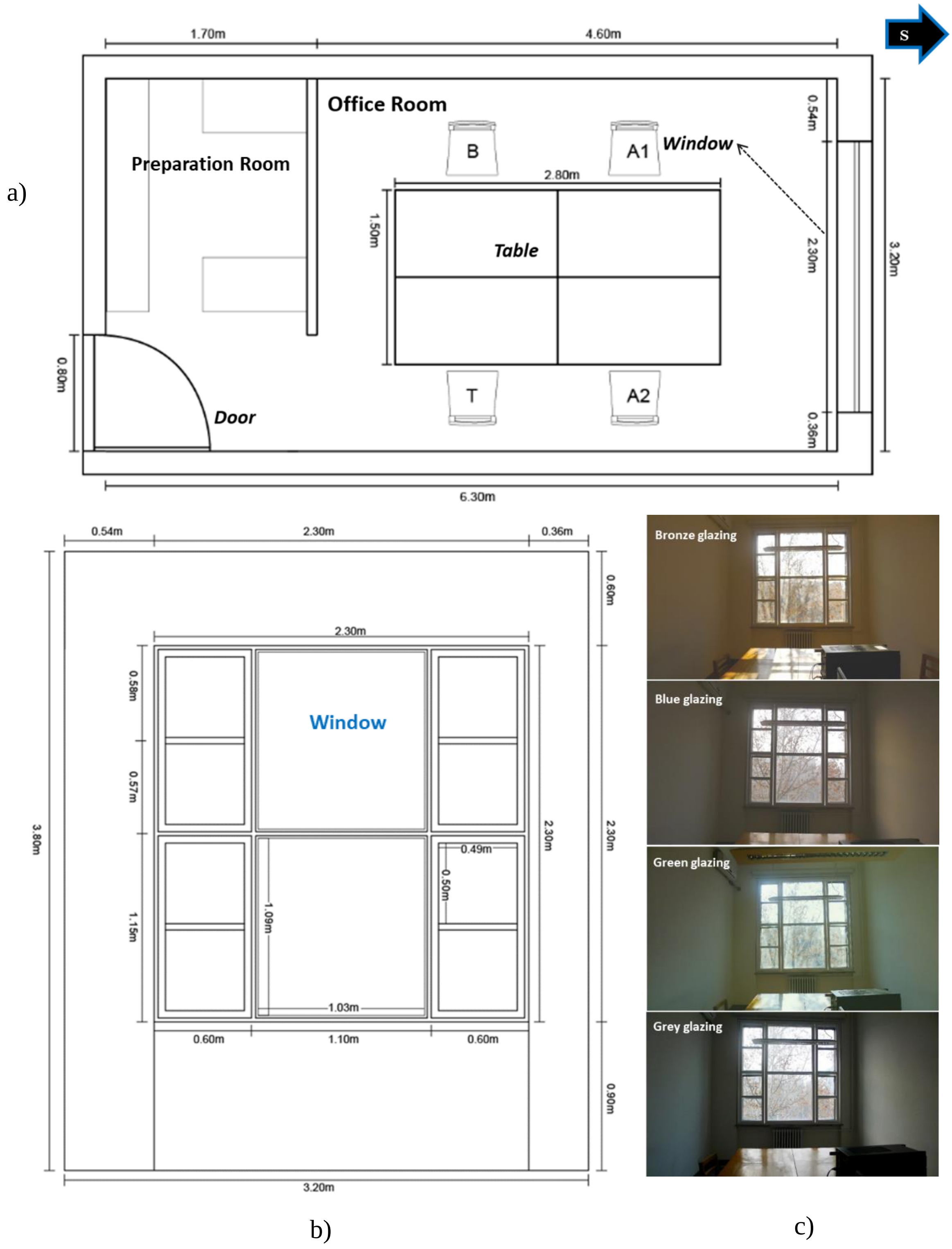

Figure 1: The office room used for the experiment; a) Plan, dimensions, and sitting positions; b) Window configurations and dimensions; c) Interior views of four glazing systems (bronze, blue, green and grey).

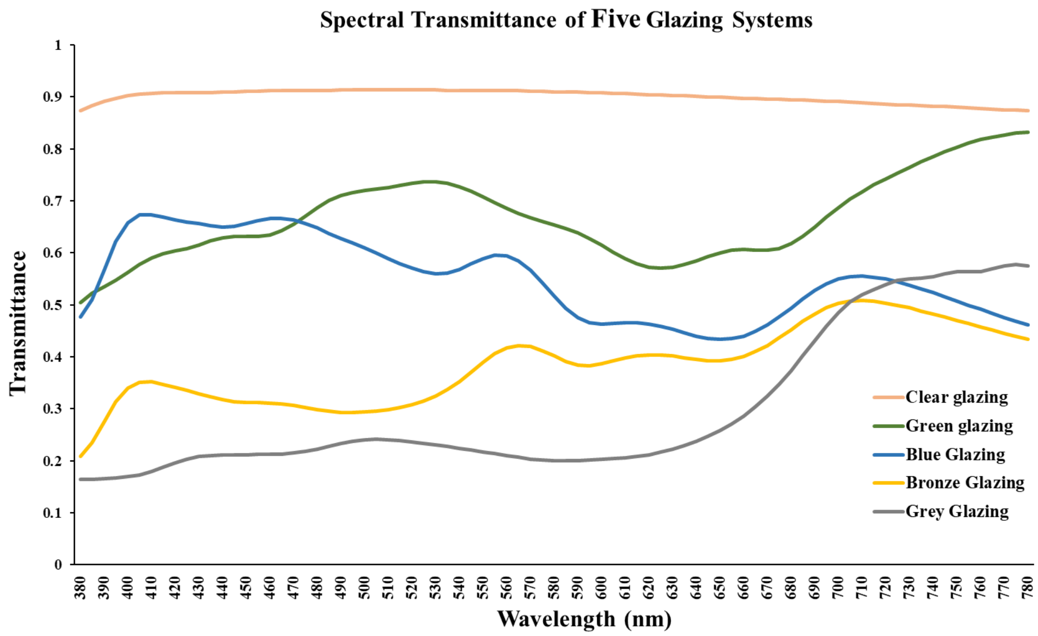

Figure 2: Spectral transmission of five glazing systems studied in this office (measured by China Academy of Building Research).

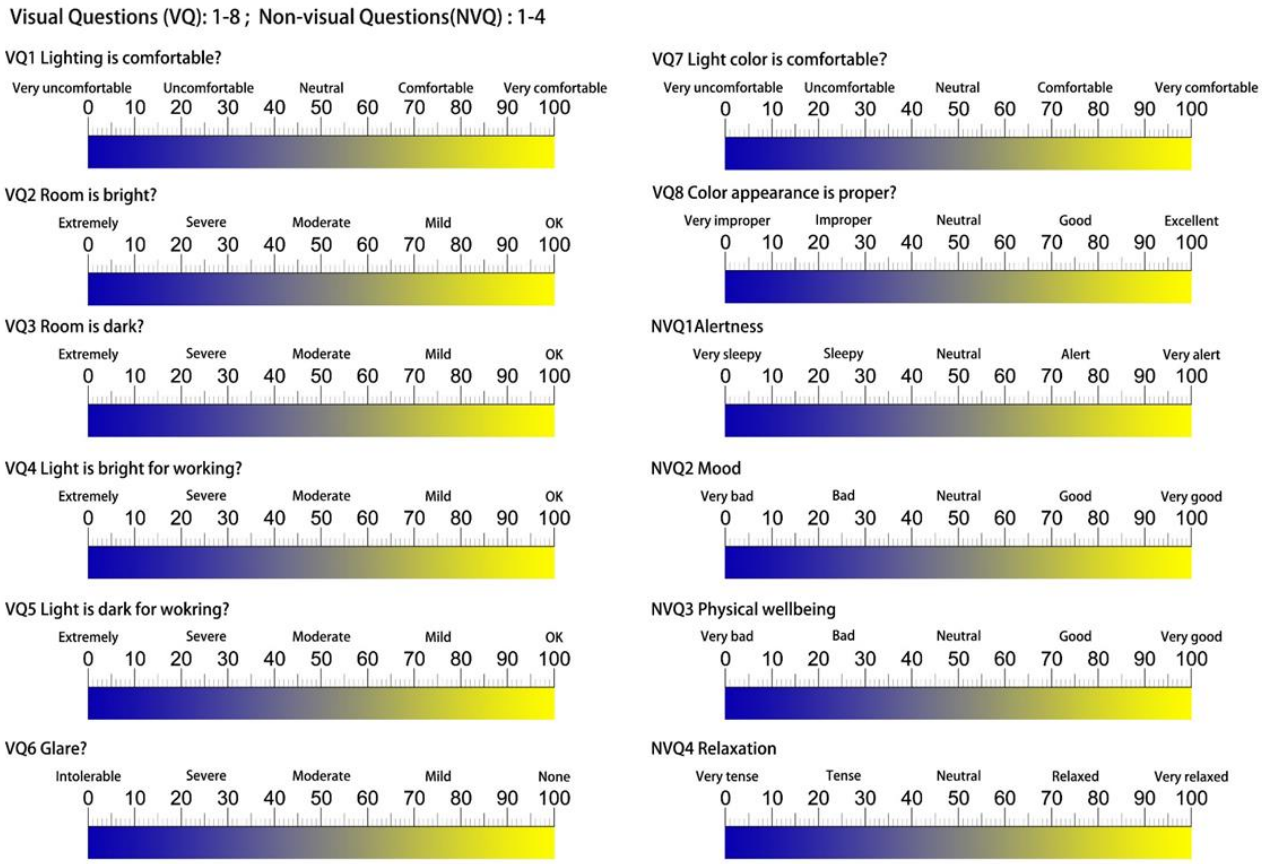

Figure 3: VAS (visual analogue scale) questionnaires: Visual questions (VQ1-8) and Non-visual questions (NVQ1-4).

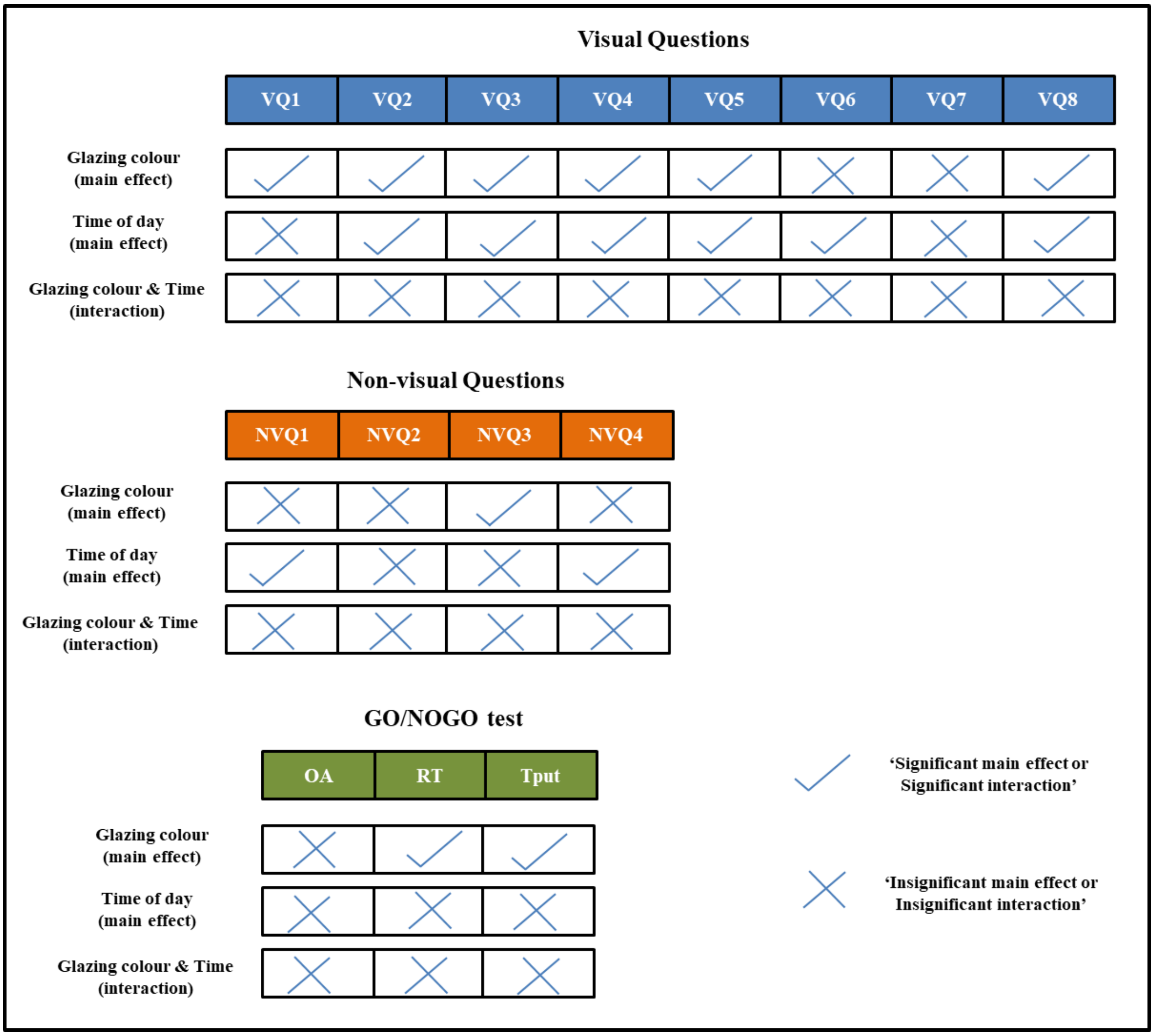

Figure 4: Graphical summary of the ANOVA results of subjective assessment and GO/NOGO test.

Figure 5: Normalized feedback of VQ1, VQ2, and VQ3 with five glazing systems and various times of day: Mean scores (Sig. p<0.05).

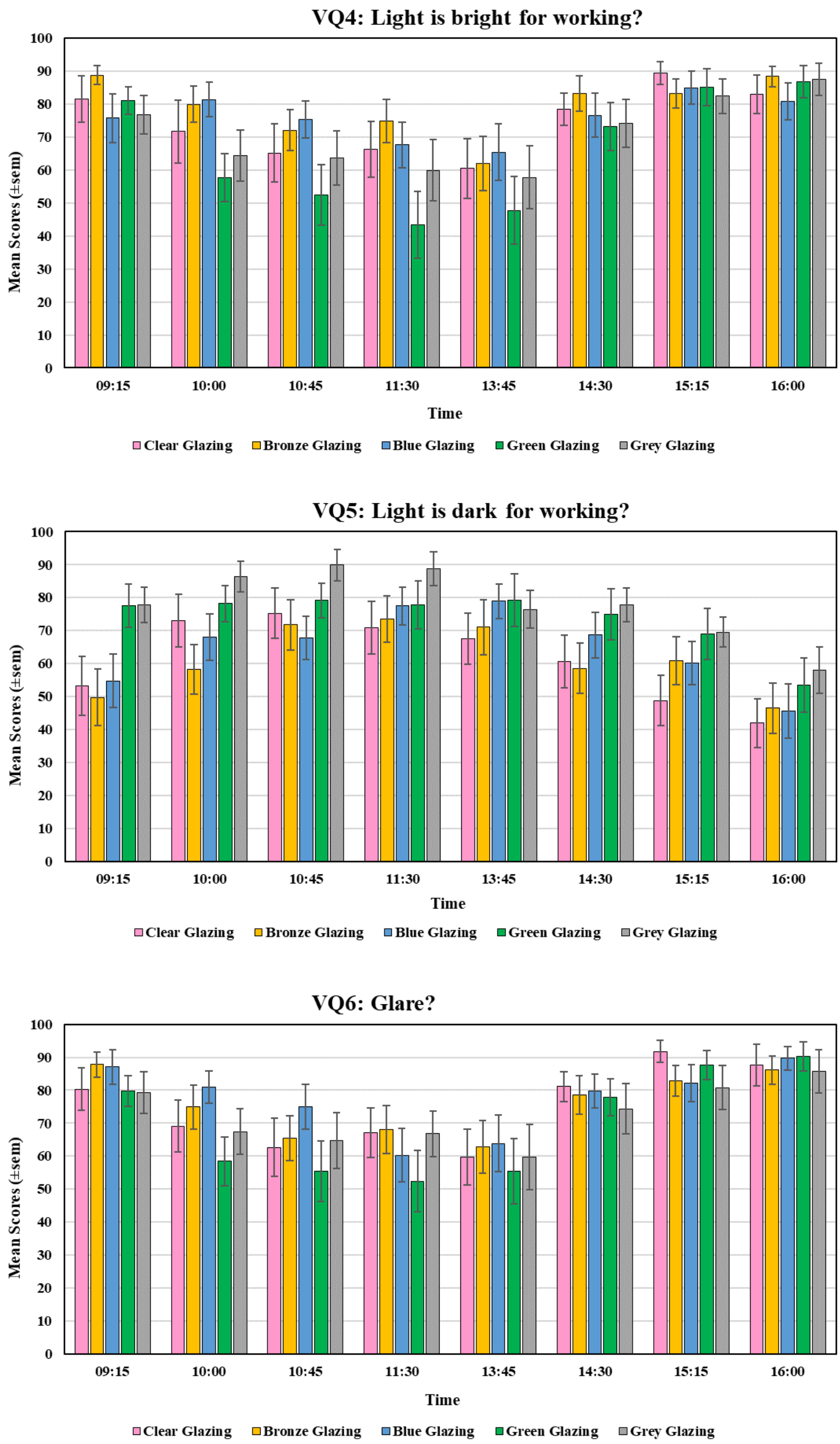

Figure 6: Normalized feedback of VQ4, VQ5, and VQ6 with five glazing systems and various times of day: Mean scores (Sig. $p<0.05$).

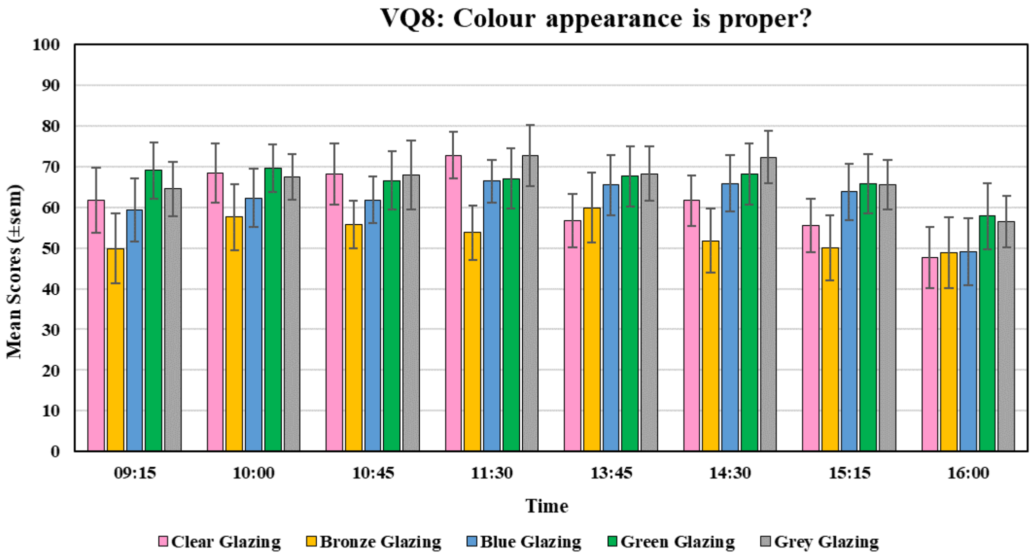

Figure 7: Normalized feedback of VQ8 with five glazing systems and various times of day: Mean scores (Sig. p<0.05).

Figure 8: Normalized feedback of NVQ1, NVQ3, and NVQ4 with five glazing systems and various times of day: Mean scores (Sig. $p<0.05$).

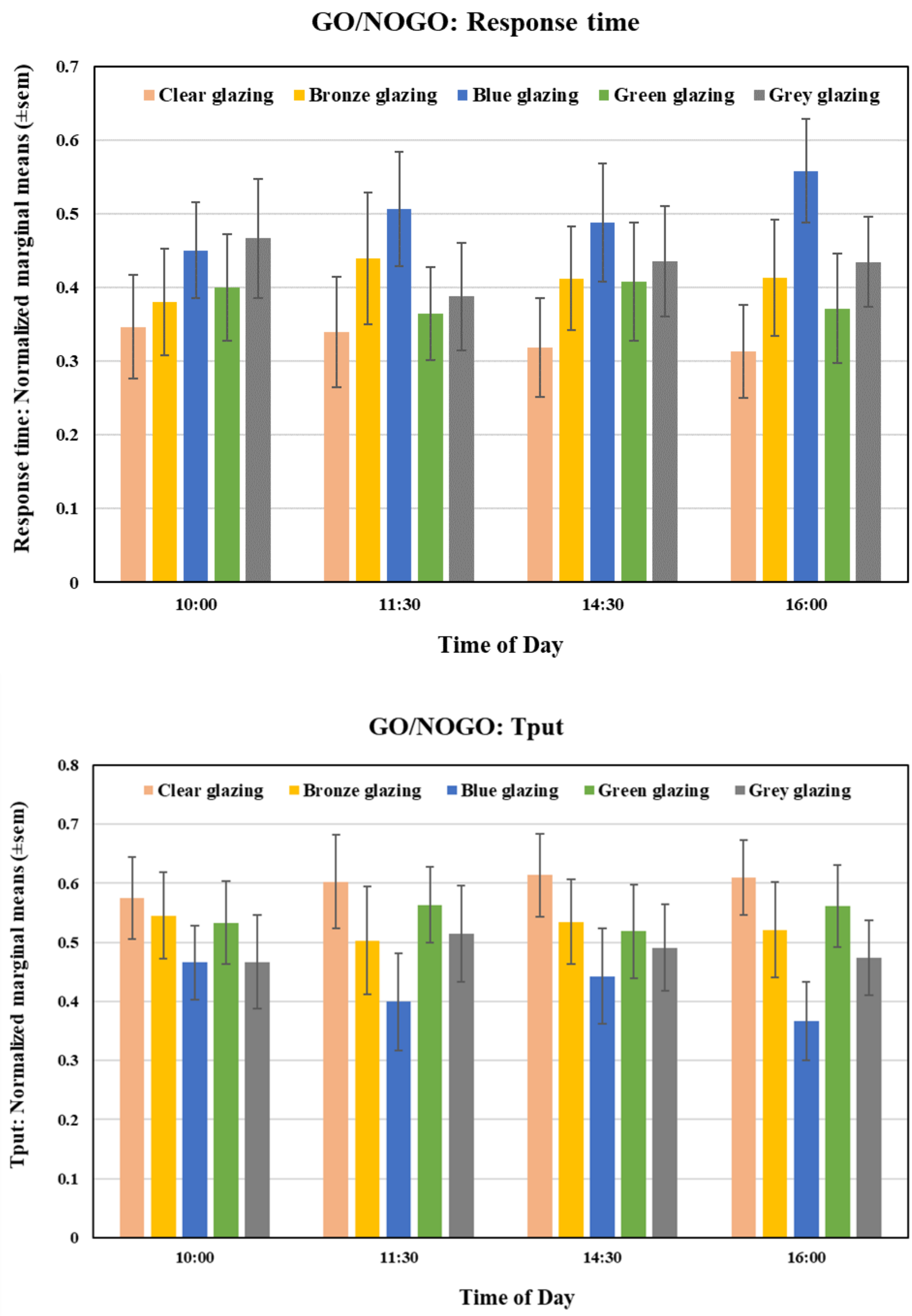

Figure 9: Testing results of GO/NOGO with five glazing systems and four times of day: normalized mean (±SEM) values of response time (RT). (Sig. $p<0.05$).