# Studying the Impact of Colored Glazing Systems on Visual and Non-visual Performances in a Daylit Office

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**Abstract**

This article presents a full-scale survey of the impact of colored/neutral glazing systems on occupants' visual and non-visual functions, as well as working performance in a daylit office in Beijing, China. Five glazing systems were investigated during a heating season from 17 November 2016 to 11 January 2017. Lighting measurements and subjective assessments were conducted to study the relationship between lighting conditions, glazing types, and visual and non-visual performances. Several key findings were achieved as follows: 1) According to visual performances, the blue glazing could be the best solution while the bronze glazing tends to be less acceptable; both grey and green glazing systems did not show significant differences from the clear glazing. 2) No clear divergences of non-visual performances can be found between various colored/neutral glazing systems. 3) The circadian light (CL) has an obvious link to occupants' non-visual performances. 4) Participants' working performance in a short-term GONOGO test will become worse when the blue glazing system is applied.

*Keywords: Colored glazing; Visual and non-visual performances; Daylit office; Heating season; Beijing*

## 1. Introduction

Daylighting has been recognized as a critical environmental factor in office buildings, due to its significant effects on workers' performances such as productivity, psychological and physiological aspects (Veitch et al., 2004; Aries et al., 2015). Studies of daylight's impact on occupants have recently become a focus in offices. Using a survey of ten office buildings in the Netherlands, Aries et al. (2010) found that workers' visual comfort and well-being can be substantially linked to configurations and installations of the external window, which can determine indoor daylighting conditions and view. Borisuit et al. (2014) pointed out that office occupants prefer to work with the occurrence of daylighting in terms of visual and non-visual functions. Another office survey in both winter and summer periods enhanced the importance of daylight availability and its positive influences on productivity, mood and sleep quality (Figueiro & Rea, 2016). As highlighted in a new report (Ticleanu & Littlefair, 2017) and a short commentary (Figueiro, 2013), nevertheless, more proofs would still be required to justify how daylight regulates sleep and mood, especially in the working spaces.

Due to the application of coated/tinted glass, currently, colored glazing systems can be broadly found in modern office buildings across the world (SLL, 2014; BSI, 2011). The primary function of these glazing systems is to adjust the external solar gains, and therefore help bring in a proper level of indoor thermal/visual comfort. In the meantime, the effect of those coated/tinted glazing systems on visual and color perception has been noticed (Bulow-Hube, 1995). A pilot study using scale models indicated that the neutral coated glazing with a high visual transmittance can receive more acceptances (Dubois et al., 2007). On the other hand, the colored coated glazing products in the current market can possibly distort the color appearances of daylight in modern buildings (Matusiak et al, 2012). Based on scale models and subjective assessments, a study showed that there is a preference for daylight filtered through colored window glazing and that the glazing color type may have a significant effect on arousal level of office workers (Arsenault et al., 2012). This study (Arsenault et al., 2012) also revealed that the bronze glazing receives more preferences than the blue and clear glazing. In the area of artificial lighting design, the light color temperature in working places does affect occupants' performance (Bellia et al., 2015). An interesting finding has been produced through a human experiment (Sahin & Figueiro, 2013): the narrow long-wavelength / red light (2568K) can obviously increase alertness and working performance during the daytime. However, few studies have been completed so far to fully explain how the broad-wavelength daylight combined with colored glazing works on human's psychological and biological functions.

Therefore, it is still necessary to carry on more investigations on the relationship between glazing types,


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daylighting and human performance in office buildings. Based on daylighting measurements and subjective assessment, this article presents a study in a full-scale office room with various glazing systems in Beijing, China. The aim is to investigate how the colored/neutral glazing affects the human visual comfort, non-visual functions including mood, alertness, well-being and relaxation and working performance.

## 2. Methods and materials

### 2.1. Office room, study design, and participants

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

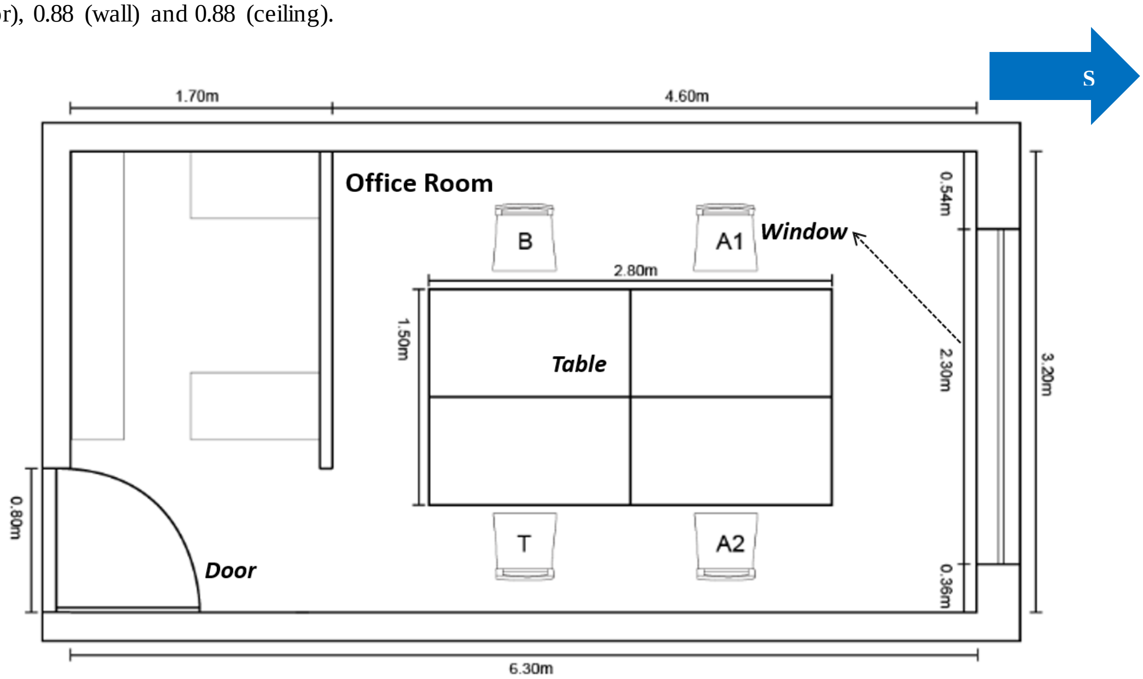


**Fig. 1: Plan, dimensions, and sitting positions of the office room studied**


**Fig. 2: Window configurations and dimensions (a); interior views of four glazing systems (blue, bronze, green and grey) (b).**

Configures and dimensions of the side window can be found in Figure 2 (a). It has a dimension of 2.3×2.3m and a two-layer structure. The external layer is composed of single clear glazing and dividers, while the internal layer adopts a removable structure with easily installed/dismantled glazing and dividers. Five types of glazing were studied including clear, blue, bronze, green and grey. They are typical products that can be found in current Chinese window market and have been widely used in modern non-domestic buildings. Except for the clear glazing, Figure 2 (b) displays pictures of the interior appearances with four glazing systems in the room. The transition spectrum of all glazing systems can be found in Figure 3. Then, overall visible transmittance (VT) values of them are 0.91 (clear), 0.55 (blue), 0.37 (bronze), 0.68 (green) and 0.22 (grey).

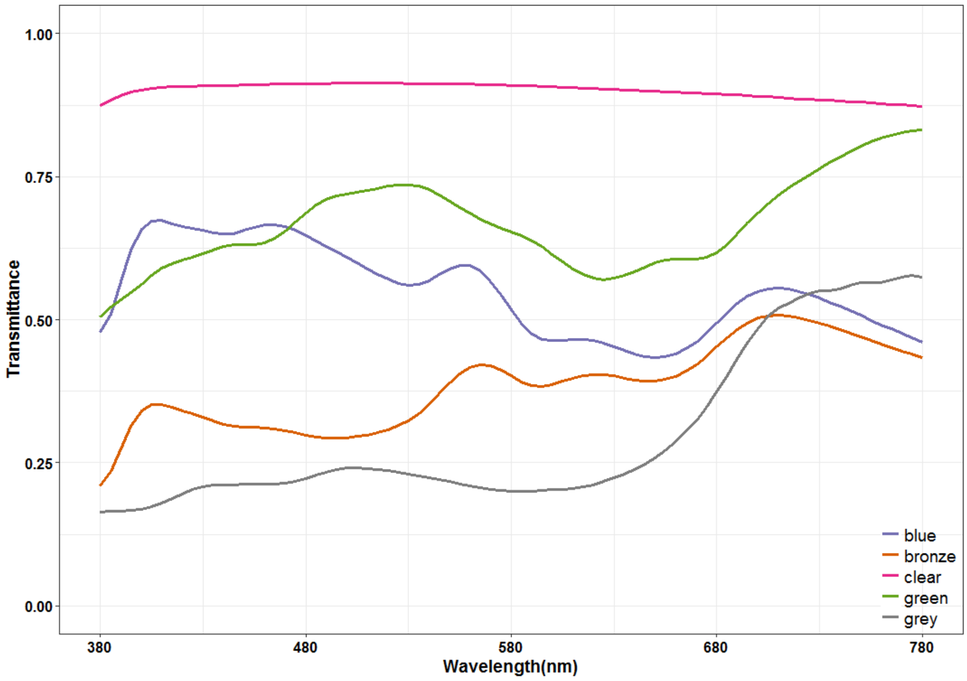


**Fig. 3: Transmission spectrum of window glazing systems used in the office**

A total of 17 participants were recruited from current students at Tsinghua University, with a mean age of 22.68 (±1.80) years. No participants should have medical and psychiatric diseases and sleep disorders. Each participant attended a five-day experiment, while only one type of glazing has been tested for each day. All participants were required to attend the 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 at the night before the testing day. During the experiment, the participants were just allowed to carry out regular office work in the office room, such as reading, writing, typing, etc. No food and drinks with caffeine or similar content can be taken on the testing day.

## *2.2. Light measurements and calculations*

The experiment has been implemented under only 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. The lighting condition was measured by a portable Illuminance Color Spectral meter (SPIC-200), in terms of three types of data: illuminance (lux), spectral distribution and correlated color temperature (CCT, K). The measured positions were the table and the vertical plane near the participant's eyes. Each meter reading was recorded every 10 minutes. Based on the collected light spectral distributions, Circadian Light (CL) and Circadian Stimulus (CS) were calculated according to a reference (Rea and Figueiro, 2016). The two values can be adopted as indicators of the nocturnal melatonin suppression due to the spectral response of the human circadian system. In addition, the indoor temperature and humidity were measured as a reference of thermal conditions.

## *2.3. Visual and non-visual assessment*

Two VAS (visual analogue scale (Monk, 1989)) questionnaires were adopted to assess the visual and non-visual performances of participants. A paper-based VAS was used as a measuring tool for each question (scale range: 0-100mm).

The visual assessment questionnaire is composed of six questions: Q1, Lighting is comfortable? (0mm, extremely uncomfortable; 100mm, extremely comfortable); Q2, Room is bright? (0mm, very bright; 100mm, OK); Q3, Room is dark? (0mm, very dark; 100mm, OK); Q4, Glare? (0mm, intolerable; 100mm, no); Q5, Light color is comfortable? (0mm, extremely uncomfortable; 100mm, extremely comfortable); Q6, Color appearance is proper?

(0mm, absolutely not; 100mm, perfect). Four questions were given in the questionnaire for assessing non-visual performances as follows: Q1, Alertness (0mm, extremely sleepy; 100mm, extremely alert); Q2, Mood (0mm, very bad; 100mm, very good); Q3, Physical well-being (0mm, very uncomfortable; 100mm, very comfortable); Q4, Relaxation (0mm, very tense; 100mm, very relaxed). Each participant was asked to complete the two questionnaires every 45 minutes. Thus, a total of 16 questionnaires would be collected from each participant in each testing day. The feedbacks were statistically analyzed using IBM_SPSS(v23).

### 2.4. Working performance test

Participants' working performances in this experiment were tested using a computer GONOGO tool. This tool was produced by the authors according to fundamental GONOGO theories (Kreutzer et al., 2011). A GONOGO test is generally used to measure a participant's capacity for sustained attention and response control (Kreutzer et al., 2011).

In this study, the GONOGO test totally followed the method used in a human performance experiment (Sahin et al., 2014). Based on participants' responses via a computer mouse, this test lasted around 10 minutes. In each 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 test time while only 30% of the time will be given to the frowning face. Once the participant clicks on the mouse, the face will disappear and the time from the face 'appear' to 'disappear' will be recorded. If the participant's response time is longer than 1 second, the face will vanish and therefore a 'miss' was recorded. In addition, a 'false alarm' will be recorded if the participant clicked the mouse before the face appears. In this study, each participant attended a GONOGO test every 90 minutes.

As mentioned in the experiment (Sahin et al., 2014), four GONOGO scores were adopted to measure the working performance: overall accuracy, mean response time, mean response time of the best 10% of response times, mean response time of the worst 10% of response times. A new value named as Tput was adopted in order to statistically analyze the collected data (Sahin et al., 2014), and it can be calculated through the algorithm: 100 × (# of valid responses) / (# of total responses) / median of the response times. A valid response used in the calculation did not include 'miss' and 'false alarm of an incorrect face shape'. Therefore, three Tput values can be achieved such as for a total test (Tput), the best 10% of response times (bTput) and the worst 10% of response times (wTput).

## 3. Results and discussions

This section includes results and discussions from lighting measurements, subjective assessments of visual and non-visual performances, as well as working performances using GONOGO in the office with various glazing systems.

### 3.1. Daylighting and color conditions

Figure 4 displays mean values of vertical illuminance and CCT near participants' eyes in terms of varying times and glazing types. Most of the time the grey and green glazing systems have higher illuminance levels than other types. The mean values of illuminance are 1454.3lux (±237.0) and 1407.7lux (±189.2) for grey and green glazing respectively. On the other hand, the lowest illuminance levels can be found with the blue and bronze glazing as follows: 701.1lux (±101.6) and 620.2lux (±86.3). The daylighting performance of clear glazing is in between (1025lux (±190.57)). It can be clearly noticed that a higher visual transmittance of glazing does not necessarily bring in a higher indoor illuminance. Certainly, external sky conditions are more critical. From around 10:00 to 15:00 all the glazing systems see a vertical illuminance above 500lux, whilst a higher illuminance (>1000lux) can be only found in a time slot of 12:00 -- 14:00. In the late afternoon (15:00—16:00) all the glazing types give rise to a lower illuminance level (<500lux). In general two peaks of illuminance variation occur at 10:45 and 13:45 for most of the glazing systems.

As for the mean values of CCT of light near participants' eyes, no big differences can be found in the daily testing time from 9:15 to 16:00. The blue glazing has the highest mean CCT of 5395.1K (±36.0), which could result in a relatively cold/blue lighting atmosphere. It is normal that the lowest mean CCT of 3986.2K (±54.8) occurs with the application of bronze glazing. This value will not be considered as 'warm', but 'neutral' or 'white'. However, the use of green, grey and clear glazing systems can lead to mean CCT values between 4000K and 5000K. A light color in this range tends to be called as 'cold white'. Interestingly the green and grey glazing systems achieve a similar CCT value: 4792K (±30.4) for green glazing; 4724.5K (±53.0) for grey glazing. The clear glazing, nevertheless, has a slightly lower mean CCT of 4443.9K (±27.2). Accordingly, the three glazing systems might produce a similar light atmosphere in this office room during the testing time.

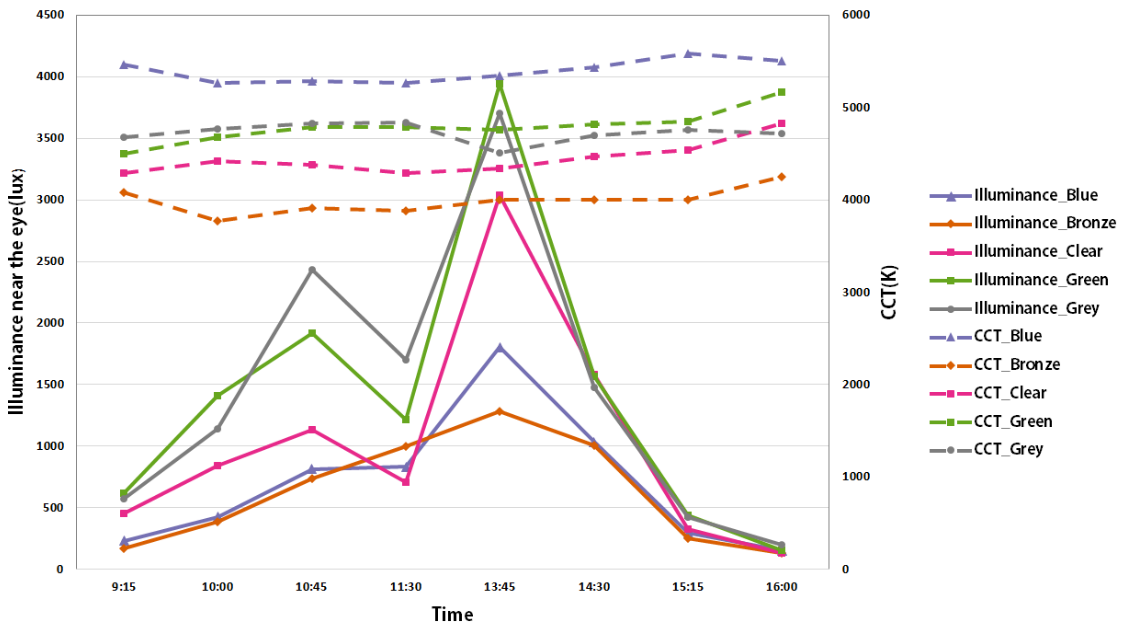


**Fig. 4: Mean values of vertical illuminance and CCT (measured near the eyes of participants)**

## *3.2. Visual performance*

A 'five glazing types × eight times' repeated measures of variance (ANOVA) was performed using the feedback from the visual performance questionnaire including six questions (see section 2.3). A Post Hoc method (Least Significant Difference (LSD)) was used to further compare the main effects and interactions. The planned comparisons were performed to investigate whether the visual performances of five glazing types were significantly different from each other. All statistical analyses were completed using IBM SPSS (v23.0). The significance can be achieved based on $p < 0.05$.

Figure 5 & 6 display the impact of glazing type and times on the six questions of visual performance (ANOVA). For the visual performance, the assessment of seventeen subjects reveals a significant impact of glazing types on Q2 (Brightness) [$F(4, 678) = 4.468$, $p = 0.001$], Q3 (Darkness) [$F(4, 678) = 9.793$, $p < 0.001$], Q4 (Glare) [$F(4, 678) = 3.196$, $p = 0.013$ ], Q6 (Color appearance) [$F(4, 678) = 3.035$, $p = 0.017$]. The visual comfort (Q1) and color comfort (Q5) have no clear relationship with the glazing type ($p > 0.05$). Similarly, the time takes clear effects on the visual performances of Q2 (Brightness) [$F(7, 678) = 11.371$, $p < 0.001$], Q3 (Darkness) [$F(7, 678) = 9.465$ , $p < 0.001$], and Q4 (Glare) [$F (7, 678) = 12.470$, $p < 0.001$]. No significant influence of time can be found for the Q1, Q5 and Q6 ($p > 0.05$). In addition, no significant interaction effects between glazing type and time were proved according to the feedback of six visual performance questions.

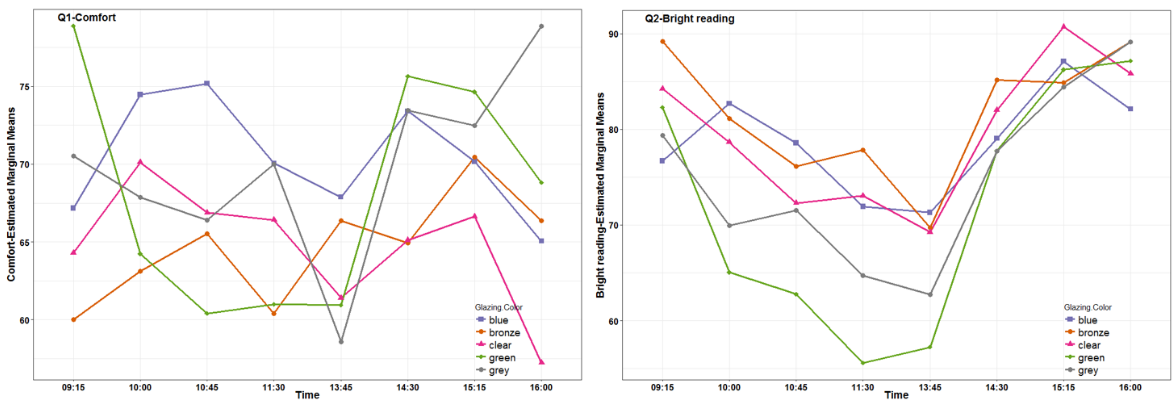


**Fig. 5: Subjective assessments of visual performance (Q1--2): the impact of glazing types and time**


**Fig. 6: Subjective assessments of visual performance (Q 3--6): the impact of glazing types and time**

Table 1 gives the multiple comparisons of visual performances between various glazing types (Post Hoc, LSD). Only the results with a significant difference have been presented ($p < 0.05$). For Q1 (comfort), the score of blue glazing is higher than both bronze and clear glazing ($p < 0.05$), whilst the score of bronze glazing is significantly lower than the grey glazing ($p < 0.05$). Even though the illuminance levels of blue and bronze glazing are similar, participants feel more comfortable with the occurrence of blue glazing. When compared with the clear type, the blue glazing can still receive a higher acceptance rate. The first feedback of comfort would support that participants in this office were more sensitive to the glazing's color than its visual transmittance and illuminance level. The questions Q2-4 focuses on the visual comfort and their feedback shows a similar statistical result. Compared with the green and grey glazing, generally, the blue, bronze and clear glazing would bring in a relatively darker lighting space and the lower risk to get glare problems in this office ($p < 0.05$). Taking Q2 (brightness) as an example, scores of blue, bronze and clear glazing are significantly higher than those of green and grey glazing. Interestingly, the clear glazing tends to deliver a darker lighting condition than the blue glazing ($p = 0.034$), although the former receives 40% higher illuminances than the latter. For the Q5 (color comfort), the only significant difference can be found between the blue, bronze and green glazing. Both blue and green glazing will give the participants a more comfortable color environment than the bronze type ($p = 0.026$ or $0.04$). However, no clear differences of color comfort were achieved between the clear glazing and others ($p > 0.05$). On the contrary, the color appearance (Q6) shows an obvious difference between the bronze glazing and the blue, clear, green, grey glazing systems. The participants would agree that the bronze glazing can have a higher possibility to distort a normal color appearance even compared with the green glazing.

As regards Figure 5, 6 and Table 1, main effects of the time between various glazing systems also have some clear differences. It can be revealed that participants feel less comfortable (Q1) when the time is at 13:45 than 14:30 ($p = 0.023$) and 15:15 ($p = 0.013$). Also, participants would feel brighter when it is approaching the time 12:00, and therefore complaining of glare will start to increase at the same time. Also, the same feedback occurs for the color comfort (Q5): participants would feel less comfortable about the light color at 13:45 than other times, such as 10:00 ($p = 0.37$), 10:45 ($p = 0.42$), 14:30 ($p = 0.18$), 15:15 ($p = 0.15$). These findings indicated that under a higher illuminance level participants' comfort may not be linked with glazing color.

**Tab. 1: Post-Hoc LSD: multiple comparisons of visual performances between glazing types (Sig. p < 0.05)**

| Dependent Variable | (I) Glazing type | (J) Glazing type | Mean Difference (I-J) | Std. Error | Significance |
|---|---|---|---|---|---|
| Q1-comfort | blue | bronze | 6.00 | 2.603 | .022 |
| | blue | clear | 5.88 | 2.603 | .024 |
| | bronze | grey | -5.13 | 2.599 | .049 |
| Q2-brightness | blue | green | 6.77 | 2.638 | .011 |
| | bronze | green | 9.88 | 2.634 | .000 |
| | bronze | grey | 6.71 | 2.634 | .011 |
| | clear | green | 7.74 | 2.634 | .003 |
| Q3-darkness | blue | clear | 5.96 | 2.804 | .034 |
| | blue | grey | -9.23 | 2.804 | .001 |
| | bronze | green | -8.49 | 2.799 | .003 |
| | bronze | grey | -12.90 | 2.799 | .000 |
| | clear | green | -10.79 | 2.799 | .000 |
| | clear | grey | -15.19 | 2.799 | .000 |
| Q4-glare | blue | green | 6.61 | 2.649 | .013 |
| | blue | grey | 5.53 | 2.649 | .037 |
| | bronze | green | 6.01 | 2.644 | .023 |
| | clear | green | 6.98 | 2.644 | .009 |
| | clear | grey | 5.90 | 2.644 | .026 |
| Q5-color comfort | blue | bronze | 5.72 | 2.563 | .026 |
| | bronze | green | -5.26 | 2.558 | .040 |
| Q6-color appearance | blue | bronze | 5.32 | 2.368 | .025 |
| | bronze | clear | -5.46 | 2.364 | .021 |
| | bronze | green | -6.21 | 2.364 | .009 |
| | bronze | grey | -7.68 | 2.364 | .001 |

For the visual assessment, the application of blue glazing can generally benefit the occupants' performance and comfort, even compared with the normal glazing, i.e. clear product. In the contrast, the bronze glazing would receive the lowest acceptance rate when evaluating the visual performance. Other glazing types have no clear differences including green, grey and clear glazing. A higher illuminance level after 12:00 might increase occupants' discomfort.

### 3.3. Non-visual performance

Similarly, an analysis of the subjective feedback under 'five glazing types × eight times' were performed using ANOVA and LSD for the non-visual performance assessment including four questions (Q1-4). In addition, a correlation analysis (Pearson) was implemented between the circadian light and stimulus (Rea and Figueiro, 2016), and the four aspects of non-visual function. The significance can be achieved based on $p < 0.05$.

Figure 7 gives the subjective assessments of non-visual performance (Q1--4): the impact of glazing types and time. Different from the visual assessment discussed above, the ANOVA analyses exposed that there are no significant main effects of glazing type or time on the Q1 (alertness), Q2 (mood), Q3 (physical-wellbeing), and Q4 (relaxation). Also, it has not been found a clear interaction effect between glazing type and time exists. In Table 2, the LSD analyses show some differences of non-visual performance between various glazing systems. For the Q3 (physical well-being), scores of blue glazing are significantly higher than the clear one ($p = 0.035$). The blue glazing could make participants feel more comfortable than the clear type. Compared with the grey glazing, the clear glazing scores higher for the Q4 (relaxation) ($p = 0.046$). It could be reasonable that a relatively lower illuminance brought by the clear glazing would make occupants feel more relaxed. Based on both Figure 7 and Table 2, furthermore, it can be found that the alertness (Q1) can achieve a higher level at the time 11:30 than the times 09:15 (p = 0.030), 13:45 (p = 0.14), 14:30 (p = 0.005) and 16:00 (p = 0.003). This indicates participants tend to be alerted with the time approaching the noon. At the time 13:45, a lower physical wellbeing (Q3) occurs compared with the time 15:15 (p = 0.014). This could be explained by one fact that these Chinese students would feel sleepy and tired at around 13:45 (a routine nap time for university students in China). The assessment of visual performances also shows a similar result as this finding.

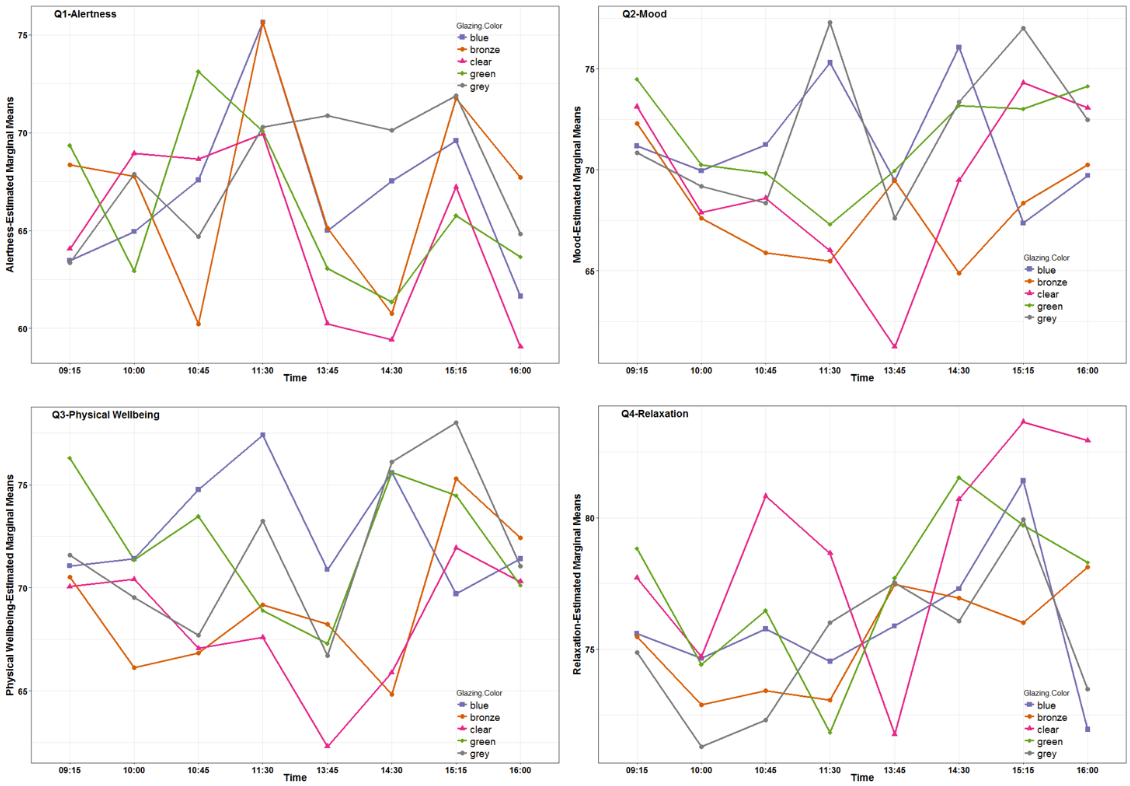


**Fig. 7: Subjective assessments of non-visual performance (Q1--4): the impact of glazing types and time**

**Tab. 2: Post-Hoc LSD: multiple comparisons of non-visual performances between glazing types (Sig. p < 0.05)**

| Dependent Variable | (I) Glazing type | (J) Glazing type | Mean Difference (I-J) | Std. Error | Significance |
|---|---|---|---|---|---|
| Q3-physical wellbeing | blue | clear | 4.48 | 2.114 | .035 |
| Q4-relaxation | clear | grey | 3.68 | 1.843 | .046 |

**Tab. 3: Correlations between daylighting conditions and non-visual performances (Pearson Correlation)**

| | | Alertness | Mood | Physical well-being | Relaxation |
|---|---|---|---|---|---|
| Circadian light (CL) | Correlation coefficient | -.041 | -.136** | -.153** | -.147** |
| | Sig. (2-tailed) | .292 | .000 | .000 | .000 |
| | N | 679 | 679 | 679 | 679 |
| Circadian stimulus (CS) | Correlation coefficient | .002 | .003 | .013 | -.066 |
| | Sig. (2-tailed) | .962 | .942 | .739 | .085 |
| | N | 679 | 679 | 679 | 679 |

Table 3 presents a correlation analysis (Pearson) between circadian light and stimulus (CL & CS) and non-visual performances including four aspects. A clear link can be found between the circadian light, and mood (Q2, correlation coefficient = -0.136, $p < 0.001$), physical well-being (Q3, correlation coefficient = -0.153, $p < 0.001$) and relaxation (Q4, correlation coefficient = -0.147 $p = 0.001$). A higher level of circadian light may indicate a lower score of the three aspects. However, the circadian stimulus does not show any significant relevance to the three non-visual factors above ($p > 0.05$). In addition, the circadian light and stimulus have no clear relationship with the participants' alertness ($p > 0.05$). These analyses supported one fact that the Circadian Light should be used as an indicator of the non-visual effect of light instead of illuminance and CCT (Rea and Figueiro, 2016).

### *3.4. Working performances*

An analysis of 'five glazing types × four times' ANOVA and LSD was performed for the GONOGO results (Figure 8 & Table 4). It has been found in Figure 8: there are significant main effects of glazing types on the 'mean response time' [$F(4, 339) = 2.246$, $p = 0.064$] and the 'Tput' [$F(4, 339) = 3.142$, $p = 0.015$]; however, no clear impacts from the glazing types can be found for the 'b-Tput', 'w-Tput', 'accuracy', 'average of best 10% response time', and 'average of worst 10% response time'. In addition, the main effect of time and the interaction effect between glazing types and time are not significant according to the working performance. The significance can be achieved based on $p < 0.05$.

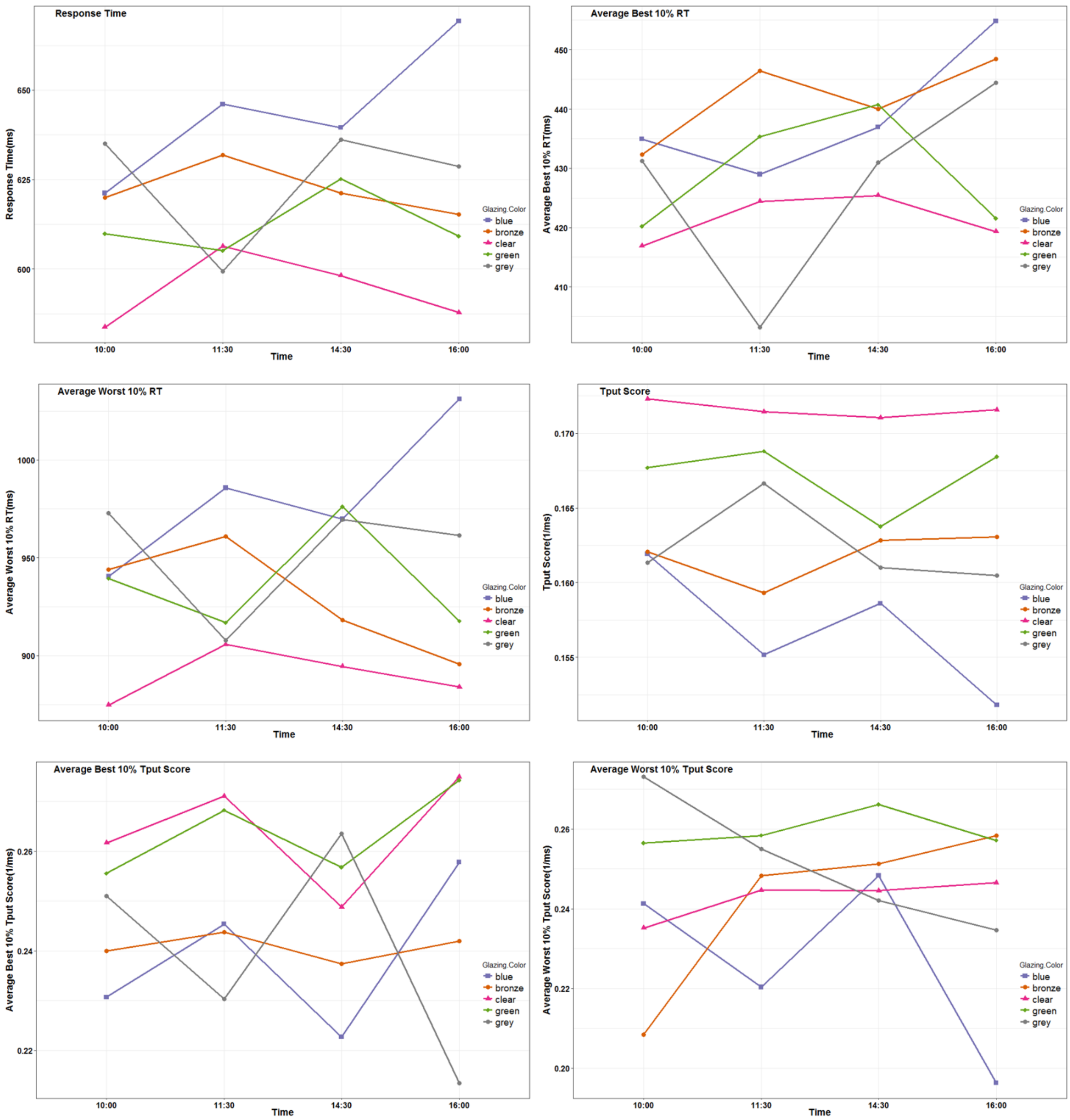


**Fig. 8: Subjective assessments of GONOGO working performance: the impact of glazing types and time**

**Tab. 4: Post-Hoc LSD: multiple comparisons of working performances between glazing types (Sig. p<0.05)**

| Dependent Variable | (I) Glazing type | (J) Glazing type | Mean Difference (I-J) | Std. Error | Significance |
|---|---|---|---|---|---|
| accuracy | blue | clear | -.018846 | .0093160 | .044 |
| | bronze | clear | -.020273 | .0093160 | .030 |
| | clear | grey | .018703 | .0093160 | .046 |
| mean response time | blue | clear | 50.007639 | 17.2499604 | .004 |
| average 10% best response time | bronze | clear | 20.289869 | 9.1630131 | .028 |
| average 10% worst response time | blue | clear | 92.094608 | 36.0994601 | .011 |
| Tput | blue | clear | -.014707 | .0044735 | .001 |
| | blue | green | -.010298 | .0044735 | .022 |
| | bronze | clear | -.009767 | .0044735 | .030 |
| | clear | grey | .009216 | .0044735 | .040 |
| w-Tput | blue | green | -.032999 | .0135124 | .015 |

As shown in Table 4, the performance differences with various glazing systems are given (only results with a significance < 0.05 are available). The accuracy of clear glazing is higher than blue glazing (p = 0.044), bronze glazing (p = 0.030), and grey glazing (p = 0.046). Compared with clear glazing, blue glazing has less mean response time (p = 0.04) and average 10% worst response time (p = 0.011). These indicate that the blue glazing helps participants deliver a quicker response, but a lower working accuracy. The clear glazing nevertheless gives rise to an opposite result. Compared to clear glazing, bronze glazing can help to reduce average 10% best response time. However, no clear difference of mean response time can be found in the two glazing systems. As for the Tput, the clear glazing shows significantly higher scores than blue glazing (p = 0.001), bronze glazing (p = 0.030), and grey glazing (p = 0.040); the blue glazing performances worse than the green type. For the green and clear glazing, it is still unclear of which one performs better in terms of Tput. Since a higher Tput value is associated with a better working performance, the application of clear glazing seems to improve the working performance.

## 4. Conclusions

A full-scale survey in an office room was given in this article, focusing on the impact of five various glazing systems on occupants' visual, non-visual and working performances across a winter period only under the daylighting condition. The key findings can be drawn from results and discussions above:

1) For the visual assessments, the blue glazing could achieve higher performances according to visual/color comfort, glare, and color appearance; while the bronze glazing has been recognized as the least acceptable choice. The grey and green glazing did not show a significant difference from the clear glazing.

2) Generally, the five glazing systems have no big differences in terms of alertness, mood, and relaxation in the office. However, the blue glazing seems to bring in more positive effects than the clear glazing according to the performance of physical well-being.

3) This experiment has found some aspects of non-visual performances of occupants have a significant link to the circadian light (Rea and Figueiro, 2016).

4) The clear glazing could be considered as the best choice according to the working performance in this office. Even though the blue glazing would improve occupants' visual performance, its effect on the working performance should be paid attention to.

5) It could be exposed that with the occurrence of daylighting the non-visual measurements are very hard to achieve; a non-linear statistical model would be required. Except for GONOGO, more practical methods to test the human working performance (e.g. reaction time task) could be considered.

6) Under daylighting conditions, human performances (visual and non-visual aspects) relating to the light color

could be very difficult to clarify, especially when considering the fact that the color preference is linked to the cultural and ethnic backgrounds.

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## References

Arsenault, H., Hébert, Marc., Bubois, M-C. 2012. Effects of glazing colour type on perception of daylight quality, arousal, and switch-on patterns of electric light in office rooms. Building and Environment. 56, 223-231.

Aries, M. B. C., Veitch, J. A and Newsham, G. R, 2010. Windows, view, and office characteristics predict physical and psychological discomfort. Environmental Psychology. 30, 533-41.

Aries, M.B.C., Aarts, M.P.J, van Hoof, J., 2015. Daylight and health: A review of the evidence and consequences for the built environment. Lighting Research & Technology. 47, 6-27.

Bellia, L., Pedace, A., Fragliasso, F. 2017. Indoor lighting quality: Effects of different wall colours. Lighting Research & Technology. 39(3), 283-340.

Borisuit, A., Linhart, F., Scartezzini, J-L., Munch, M., 2014. Effects of realistic office daylighting and electric lighting conditions on visual comfort, alterness and mood. Lighting Research & Technology. 0, 1-18.

BSI, 2011. BS/EN 410:2011: Glass in building —Determination of luminous and solar characteristics of glazing.

Bulow-Hube, H. 1995. Subjective reactions to daylight in rooms: effect of using low-emittance coatings on windows. Lighting Res. Technol, 2: 37–44.

Bubois, M-C., Cantin, F., Johnsen, K. 2007. The effect of coated glazing on visual perception: a pilot study using scale models. Lighting Research & Technology. 39(3), 283-340.

Figueiro, M. G., Rea, M. S. 2016. Office lighting and personal light exposures in two seasons: Impact on sleep and mood. Lighting Research & Technology, 48(3), 352-364.

Figueiro, M. G. 2013. Opinion: Why field measurements of circadian light exposure are important. Lighting Res. Technol, 45, pp. 6.

Kreutzer, J. S., DeLuca, J., Caplan, B. 2011. Encyclopedia of Clinical Neuropsychology. Publisher: Springer-Verlag New York.

Matusiak, B., Anter, K.F., and Angelo, K. 2012. Color shifts behind modern glazing. Research report, Department of Architectural Design, Form and Colour Studies, NTNU, Norway.

Monk, T.H. 1989. A visual analogue scale technique to measure global vigor and affect. Psychiatry Research, 27, 89–99.

Rea, M. S and Figueiro, M. G. 2016. Light as a circadian stimulus for architectural lighting. Lighting Research and Technology.0, 1–14.

Sahin, L. & Figueiro, M.G. 2013. Alerting effects of short-wavelength (blue) and long-wavelength (red) lights in the afternoon. Physiological Behaviour, 116-117, 1-7.

Sahin, L., Wood, B. M., Plitnick, B., Figueiro, M. G. 2014. Daytime light exposure: Effects on biomarkers, measures of alertness, and performance. Behavioral Brain Research, 274, 176–185.

Ticleanu, C. 2017. Report describing initial literature review on circadian lighting. CIBSE report. www.cibse.org/knowledge/knowledge-items/detail?id=a0q0O00000CF7o9QAD. (last access: 10/09/2017).

Veitch, J. A., Charles, K. E., Newsham, G.R. 2004. Workstation design for the open-plan office. Institute for Research in Construction, National Research Council of Canada. www.nrc-cnrc.gc.ca/ctu-sc/ctu_sc_n61 (last access: 10/09/2017)