Preliminary investigation on the human response to patterned chromatic glazing

Dingming Liu[a], Mark Janos Kovacs-Biro[a], Karen Connelly[a], Fedaa Abd-AlHamid[b], Yupeng Wu[a, *]

[a] Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom

[b] Department of Architecture, Faculty of Architecture and Design, Al-Zaytoonah University of Jordan, Amman, Jordan

*Corresponding authors' Emails: Yupeng.Wu@nottingham.ac.uk

Abstract

Daylighting has been associated with improved mood, enhanced morale, increased visual comfort and reduced fatigue. Glazing with varying transmittance, colour or configuration may have significant effects on the quality and quantity of daylight within a building, thus good glazing design has posed significant challenges for building designers. Colored glazing is broadly applied in modern offices worldwide and many studies have explored the effect of this glazing on human performance. Commonly studied are chromatic glazing typologies which offer a unidirectional shift in the colour of light to either bronze or blue. This alters the spectral ability of the glazing and thus changes the indoor luminous environment. It is reported that although occupants prefer warm light, people perform better under cool light condition. This project aims to implement patterns in chromatic glazing to introduce a two-directional colour distortion to alter the colorimetric characteristics of the glazing, heavily affecting the user's perception and performance in the luminous environment. More specifically, seven different indoor luminous conditions were created using various patterned chromatic glazing (100% CAR Blue, 70% CAR Blue, 30% CAR Blue, neutral clear glazing, 30% CAR Bronze, 70% CAR Bronze, and 100% CAR Bronze) to investigate their effect on human perception using a scaled test room (1:3 scaling) to simulate office working conditions. Both subjective (questionnaire on pleasantness, comfort, alertness) and objective (an achromatic Landolt ring test and a chromatic Landolt ring test) evaluations were carried out for the proposed window conditions. The results suggest that the patterned chromatic glazing conditions create a more desirable luminous indoor environment, as well as a more efficient working environment. The 30% blue and 70% blue glazing improved feelings of visual comfort compared to the 100% blue, whilst retaining the efficiency of task completion. Meanwhile the 30%

bronze glazing increased the efficiency of task completion compared to the 100% bronze, whilst retaining the ratings for comfort and pleasantness. This implies that the design of patterned chromatic glazing which introduces the combination of two chromatic glazing may be a feasible solution to improve the indoor luminous environment.

Key Words: Smart Windows; Colored Glazing; Human Response; Visual Perception; Luminous Environment.

1. Introduction

Nowadays, humans spend nearly 85-90% of their time inside buildings [1-3], and completely immersed in indoor luminous environments. It has been proven that a luminous environment has significant effect on an occupants' performance [4-6] in terms of visual perception, working efficiency, emotional/motivational state and health [7, 8]. The luminous environment also can affect the light-induced non-visual effect which is the influence of light on the biological functions of human such as physiology, behavior, mood and alertness [9]. Window design is one of the most important factors when considering the quality of an indoor luminous environment as daylight entering any indoor environment would be filtered and altered by glazing. More specifically, the quality of an indoor luminous environment can be affected by glazing with different optical properties. These properties include varying transmittance (e.g. multiple-layer glazing, reflective glazing and low-emission glazing) which may change available illuminance [10-13] or varying colours (e.g. chromatic glazing, tinted glazing and advanced window) which may have an impact on the spectral properties of the transmitted daylight [14-16].

Previous research has mostly studied the effects of glazing transmittance and colour on the quality of indoor luminous environments by examining factors that affect occupant perception and performance. These factors have mostly consisted of, but are not limited to: visual comfort, pleasantness, alertness, light level, and working efficiency [17-22]. For example, Chen et al. [21] carried out experiments to explore the effect of glazing colour on human visual performance in terms of visual comfort, brightness and colour perception, as well as non-visual performance in terms of alertness, mood and physical comfort. It was found that blue glazing has a higher rating than that of a bronze glazing when assessing visual performance. Dubois et al. [17] did a pilot study to investigate how different types of coated glazing affected human’s visual perception. Seven factors for visual perception were tested including shadows, light level, naturalness and colouring, colour temperature, beauty and pleasantness, comfort and sharpness. Results suggested that glazing of higher transmittance was given higher ratings by occupants in relation to naturalness, beauty and sharpness. Results suggested that glazing of higher transmittance were rated more positively by occupants in relation to naturalness, beauty and sharpness. Other studies have evaluated the effects of glazing transmittance on human performance. Arsenault et al. [14] revealed that higher transmittance glazing systems were preferred by occupants for naturalness, beauty, and pleasantness. Boyce et al. [10] investigated occupants’ acceptance on the minimum glazing transmittance. And the minimum transmittance was found to be in the range between 25% and 38%.

More recent studies have assessed the effect of glazing colour on human performance since colored glazing is now broadly applied in modern offices worldwide [23, 24]. Arsenault et al [15] evaluated occupants’ perception for bronze, blue and neutral glazing systems for an 1:4 scaled office model under daylight conditions. It was found that bronze glazing was preferred by participants for pleasantness, comfort and light level. Chen et al [18] explored the effect on human performance of a range of colored glazing (clear, red, blue, bronze, green, grey and dark blue glazing) with transmittance varying from 0.17 to 0.66 in a full scale office under daylight. It was found that participants had a shorter response time and delivered better work in the medium or higher Correlated Colour Temperature (CCT) luminous environment (i.e. the luminous environment created by clear and blue glazing) [25].

Liang et al [26] investigated the influence of coloured thermochromic smart windows on visual performance and occupant comfort using a developed mock-up office lit by an artificial window. Both objective visual tasks involved Landolt charts and subjective assessments were made using questionnaires to determine subjects' response to the window system in different luminous conditions. Results showed that the experimental method is effective at determining human response to chromatic glazing. A Bronze window condition caused more errors in achromatic acuity tests than a blue window condition or a clear window condition. However, compared with the other two conditions (Clear and Blue), subjects preferred to both stay and work in the bronze window condition, which provides a warm tint and relatively natural rendering of the illuminated environment. Liang et al [27] used the same mock-office to test the influence of different thermochromic tint states on human response. Objective assessments were made including visual acuity and colour naming tasks using the coloured Landolt ring chart and a sustained attention test using a d2 test as well as subjective questionnaire assessments. It was found that across the thermochromic window conditions, no significant differences in performance were found for the visual acuity and d2 tests. However, from questionnaire, subjects reported higher alertness under blue tinted condition, while higher acceptance was reported under bronze-tinted condition. Studies also investigated the connection between colour temperatures and illumination levels on a person's impression of a space. They indicated that increasing illumination level helped to improve feelings of comfort and spaciousness, as well as increasing work efficiency and thus levels of productivity [28-30]. For instance, in one study increasing illuminance from 300 lux to 2000 lux increased the productivity levels of participants by 20%, making for a better, more efficient work environment [28]. The effect of CCT (i.e. 6000K and 2700K) with 500 lux on occupants' performance has also been investigated [31], it was reported that higher subjective vitality can be detected in the 6000 K condition in the morning while negative effect on mood can be found under 6000K condition when comparing with 2700K condition.

Referring to the findings from Arsenault et al [15] and Liang et al [26]'s study, it can be seen that occupants prefer warm luminous environment that created by bronze or orange glazing where they perceive higher visual comfort, pleasantness or brightness as compared to a cool luminous environment. However, according to Chen et al [18] and Liang et al [27]'s research, it can be found that when comparing with the warm luminous environment, occupants have better working performance (i.e. higher alertness, shorter reaction time) under a cool luminous environment that created by blue glazing. Most previous studies aimed to investigate chromatic glazing with a single colour (such as bronze, blue, clear green and red) with single coloured glazing only satisfying one of the two demands: occupants' preference or high working efficiency. But few studied the effect of multi-colour glazing on occupants' perception (i.e. the effects of single coloured glazing mixed with clear glazing to gain a two directional colour shift [20]).

There is potential to design a balanced condition between warm and cool luminousity for better user preference and efficiency of work. For example, combining coloured glazing with clear glazing will change the colorimetric characteristics of the glazing, perhaps providing a more comfortable indoor luminous environment whilst maintaining the working efficiency of the occupants. On the other hand, for the window design, it is known that aesthetics of a space can be greatly influenced by the façade pattern characteristics. Irregular façade geometry has been shown to be preferred and gain greater interest when compared to regular patterns or blinds [32, 33]. Because it was reported that occupants have higher attention on the irregular variation and triggered high interest in the scene [33]. Therefore, this project aims to implement patterns in the chromatic glazing to introduce a two-directional colour distortion to alter the colorimetric properties of the glazing, thereby affecting the user's perception and performance in the luminous environment. The specific objects are to design and characterise various patterned glazing, to test their effects on occupant's performance and perception in a mock up office and to provide recommendation for future building fenestration design. i.e. Seven different indoor luminous conditions were created using various patterned chromatic glazing (100% Cover Area Ratio (CAR) Blue, 70% CAR Blue, 30% CAR Blue, neutral clear glazing, 30% CAR Bronze, 70% CAR Bronze, and 100% CAR Bronze) to preliminarily investigate its effect on human perception using a mock up office established by Liang et al [26]. A comprehensive measurement was carried out to obtain the colorimetric properties of the designed testing environment, including the artificial window (light source), surrounding environment (internal walls) and also the task area. Then the effect of the luminous environment on participants was examined when the participants were completely immersed into the environment. Both subjective (questionnaire on pleasantness, comfort, alertness) and objective (an achromatic Landolt ring and a chromatic Landolt ring test) evaluations were carried out for the proposed window conditions.

2. Methodology

The methodology was designed to provide controlled luminous conditions to evaluate the subjective and objective responses to various patterned glazing within a mock up office. In this section, the developed test room, subjective evaluations and objective tasks were explained, followed by the designed experimental procedure. The workflow that used to demonstrate the experimental procedure is illustrated in Fig. 1. The statistical tests used to analyse the data collected in this study were also described in this section.

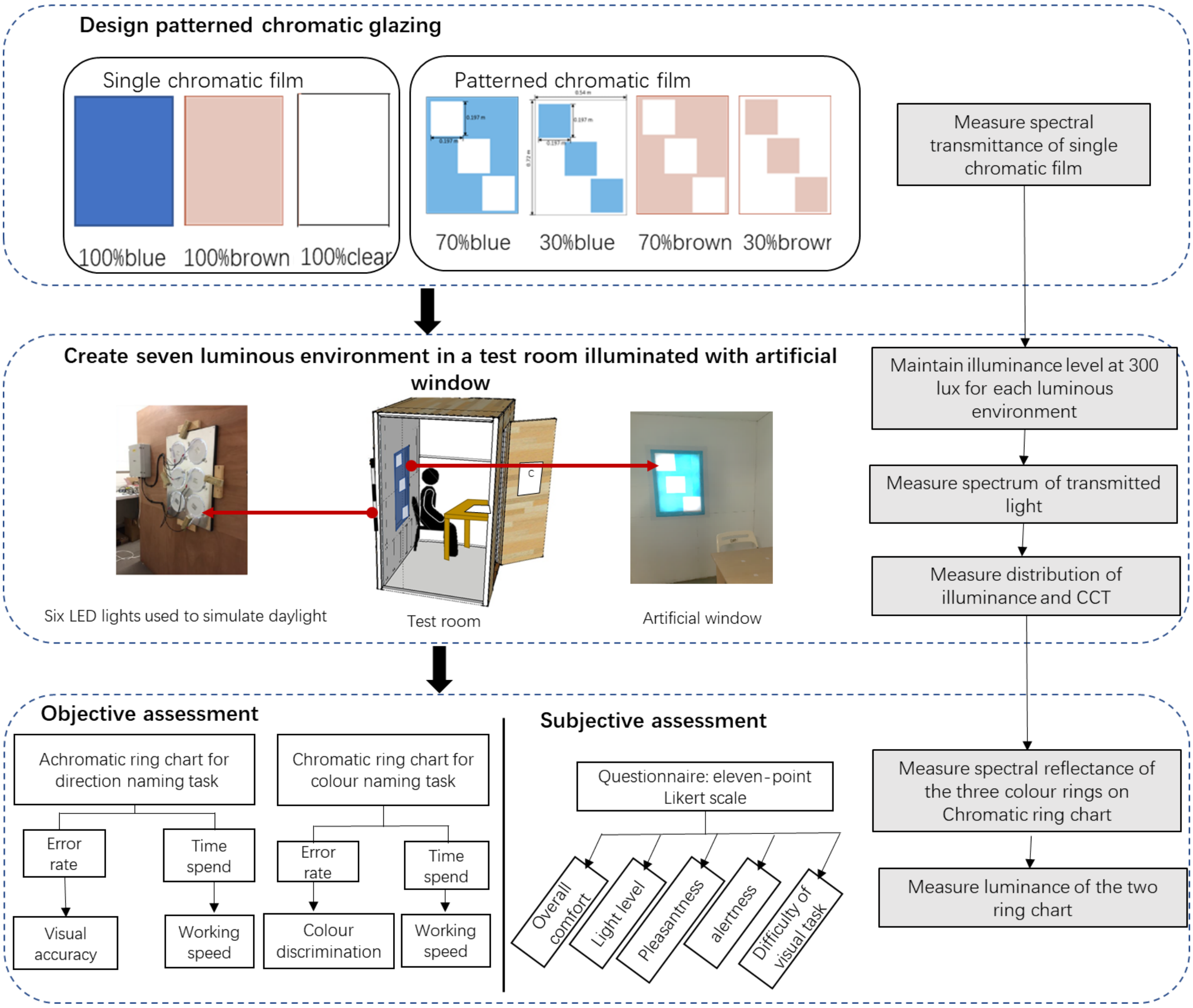
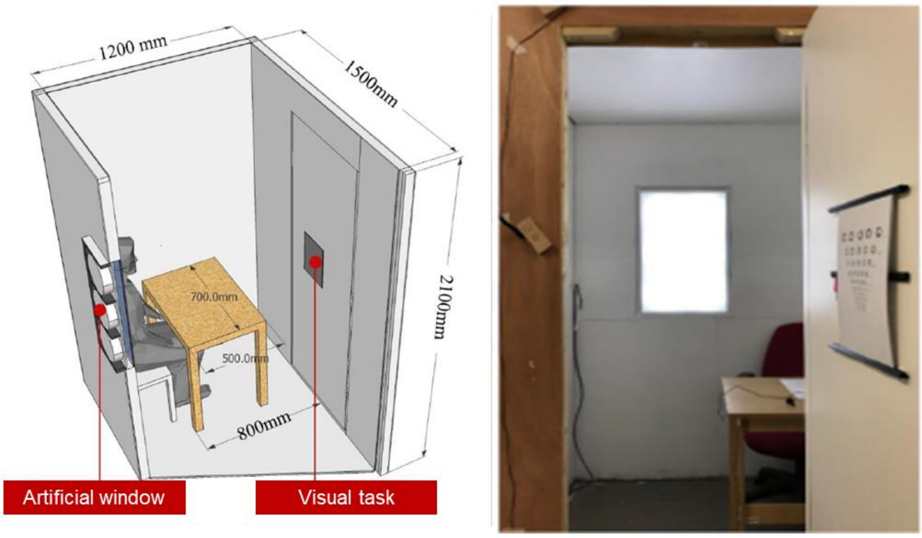


Fig. 1 The workflow for the designed experiment.

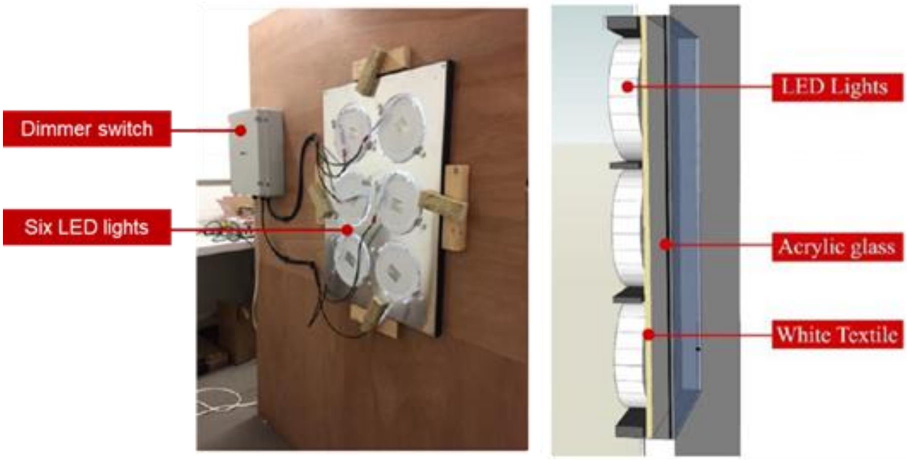
2.1. Test environment

A test room with dimensions of 1.5 m × 1.2 m × 2.1m established by Liang et al. [26] was constructed for this study in the laboratory of the Energy Technologies Building at the University of Nottingham (UK). The test room was constructed with slab of wood and has the same environmental conditions as the laboratory. The indoor temperature and humidity were constantly measured. On average, the temperature inside the chamber was constant at approximately 25°C, and humidity was in a range between 45%-55%. According to CIBSE guide A [34], a moderate comfort thermal environment has been met. Subjects were asked to complete visual tasks within this test room. The size of the experimental chamber was approximately 1/3 that of a typical 11 m^2 minimum working space, meeting the requirement for models designed for use in subject studies where subjects are expected to perceive and provide an assessment of a daylit environment [35, 36]. An artificial window consists of an array of six LED lamps behind a diffuser with a spectrum range of 400–750 nm, and generating light with a CCT close to 6500K which was used to illuminate the experimental chamber [22]..

The schematic diagram of the test room including the front view, the arrangement of LED lights and section of the artificial window were shown in Fig.2. The artificial window with dimension 0.54m × 0.72m was constructed with six LED lights controlled with a dimmer switch, white textile with diffusive properties and 3 mm acrylic glass, which was designed to supply the test room with diffused luminous environment. The LED light sources transmitted through the artificial window was used to simulate diffuse daylight transmitted through window. The interior surfaces of the test room were painted matte-white for evenly diffuse the lighting. Participants sit in the test room with back towards the artificial window and face the visual task that is fixed at the inner side of the front door (Fig. 2 (b)). They also need to complete questionnaires placed on the desk.



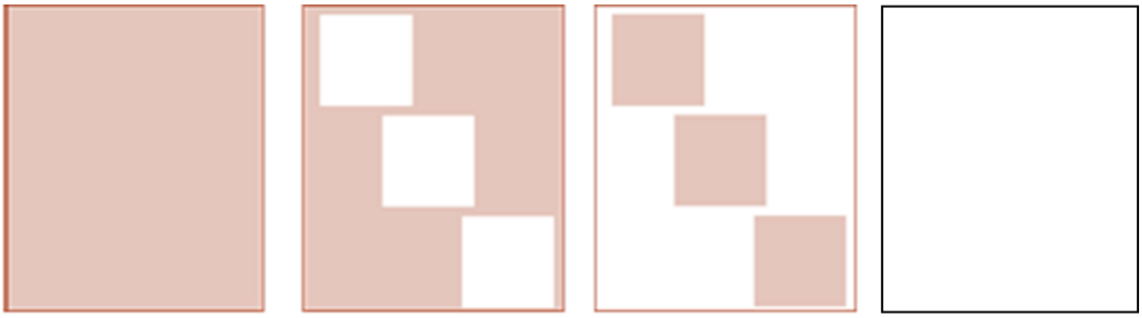
(a) (b)



(c) (d)

Fig. 2 The confirguration of (a) schematic of the test room (b) front view of test room (c) LED lights and (d) section of artificial window [26].

Films with colour pattern (shown in Fig. 3) attached to the artificial window were designed to offer different indoor luminous environments for the proposed visual performance tests. The chromatic film combined with the clear film in the form of designed patterns is shown in Fig. 3. Different patterned chromatic films were classified with their Covering Area Ratio (CAR) which is the ratio between the area of chromatic film and total area of the glazing.The patterns have been designed in the films in the form of a) 100% Covering Area Ratio (CAR), this means that glazing is covered with either 100% of bronze (named 100% bronze) or blue film (named 100% blue) respectively, b) 70% CAR, meaning 70% of the glazing is either covered with bronze (named 70% bronze) or blue film (named 70% blue) respectively, the other 30% in the shape of square patterns is clear, c) 30% CAR, whereby 30% of the glazing in the shape of square patterns is either covered with bronze (named 30% bronze) or blue (named 30% blue) film, whilst the remaining 70% of the glazing is clear, d) 0% CAR, the glazing is in clear state (named 100% clear). To summarize, there are 7 patterned films in total that were designed and used for the proposed tests.

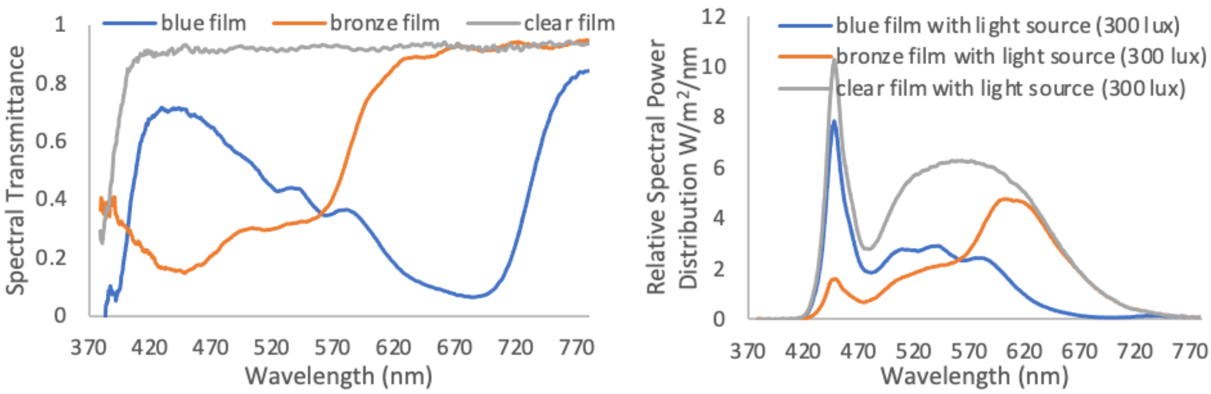


(a)100% covering area ratio (b)70% covering area ratio (c)30% covering area ratio (d)0% covering area ratio

Fig. 3 Chromatic window film patterns

2.2. Luminous Conditions

One bronze plastic film offering warm luminous and one blue plastic film providing cool luminous have been selected for this study. Fig. 4 (a) illustrates the visible spectral transmittance of the selected films measured using a calibrated Ocean Optics Spectrometer USB2000+UV-VIS. Fig. 4 (b) shows a comparison between the light spectrum transmitted through 100% bronze, 100% blue, and 100% clear films when presenting in front of the artificial window. It can be seen that blue film has a strong peak in the 450 nm (blue) region. The bronze film has lower response in the 450 nm region and a peak in the region between 600 and 630 nm.



(a) Visible transmittance of selected films (b) spectrum transmitted through the films under artificial light

Fig. 4 Spectral property of Blue, Bronze, and Clear films

Although different films would be applied to the artificial window, the illuminance within the test room would be adjusted to a similar level under all testing scenarios. To meet the indoor illuminous requirement for a typical office [34], illuminance for the horizontal surface (where is the central of the desk) and vertical surface (where is the central position for attaching Landolt ring chart on the front door) was maintained at approximately 300 lux for each of the window film condition. The indoor illuminance was adjusted by the dimmer switch of the six integrated LEDs and used a Konica Minolta CL-200A chroma-meter (accuracy ± 0.02 %) to inspect the vertical and horizontal illuminance maintain at approximately 300 lux. Even though illuminance is maintained for each scenario, the spectral properties of the transmitted light may be significantly changed with the applying of the seven patterned chromatic films. Therefore, a calibrated Ocean Optics Spectrometer USB2000+UV-VIS was used to measure the spectrum of the transmitted light as well as the distribution. The testing procedure and obtained results are given in Appendix A. It was found that the present of patterned chromatic glazing would not result non-uniformity distribution of transmitted light. It may be that the designed artificial window diffused the transmitted light whilst the interior surfaces were painted matte-white which can evenly diffuse the indoor lighting. Therefore, the transmitted light through patterned chromatic glazing can mix uniformly in the test room. Furthermore, comparing the light spectrum of pattered chromatic glazing (70%blue, 30%blue, 70%bronze and 30%bronze) with that of the single-chromatic glazing (i.e. 100%blue, 100%bronze and 100%clear), it can be seen that that light spectrums of patterned glazing are slight different due to the present of patterns. The light spectrum for the patterned chromatic glazing combined the spectral properties of the light for both clear and chromic glazing. The other colorimetric characteristics of the transmitted light including chromaticity coordinates (x,y), CCT, Duv (the shortest distance from the test chromaticity coordinates to the Planckian locus on colour space), Colour Rendering Index (CRI) and Colour Gamut Area (GAI) were calculated based on the measured spectrum for the seven luminous environments given in Table 1. In the meanwhile, illuminance (lux) and CCT (K) distribution for each scenario have also been measured, the Konica Minolta CL-200A chroma-meter (accuracy ± 0.02 %) was used to obtain these values within the test room. The measurement for the distribution of illuminance and CCT was carried out on both the desk surface and the front door. Six evenly distributed points on the two surfaces were measured by placing the sensor of the Konica Minolta CL-200A chroma-meter on each point. For measurement results of each scenario, the values of illuminance and CCT on the six points for each surface do not have remarkable variations (i.e. around 1%-2%). The values for illuminance and CCT of the central point of the vertical and horizontal surface are listed on Table 2. From Table 2, it can be seen that while keeping the illuminance at the vertical surface and horizontal surface at a near constant value respectively, approximately 4-7% deviation for the measured CCT between the horizontal and vertical surfaces was found. It is because partial of the incident light from the artificial windows on the testing plane is reflected from desk, chair, floor or the clothes during the measurement that might alter the spectrum of the incident light. Fig. 5 shows a Kruithof Chart demonstrating the expected visual appearance of the room at the measured illuminance level and CCT. The seven luminous environments are located from appearing reddish, pleasing, to bluish (condition 2 with the blue film is expected to appear significantly blue to the point it is beyond the boundaries of this commonly used chart). Pictures illustrating the tested luminous environment is presented in Fig. 6.

Table 1 Colorimetric characteristics for the seven luminous environments.

No.		x, y	CCT(K)	Duv	CRI	GAI
1	**100%clear**	0.35,0.37	5017	0.00911	82	76
2	**100%blue**	0.26,0.3	11562	0.01684	72	80
3	**100%bronze**	0.48,0.41	2444	-0.00225	86	43
4	**30%blue**	0.33,0.36	5687	0.00989	82	80
5	**70%blue**	0.31,0.34	6512	0.00991	81	84
6	**30%bronze**	0.38,0.38	4129	0.00282	87	74
7	**70%bronze**	0.4,0.39	3649	0.00031	89	69

Table 2 Illuminance level (lux) and Correlated Colour Temperature (K) under different testing scenarios

No.		Vertical surface		Horizontal surface	
		Illuminance (lux)	**CCT (K)**	**Illuminance (lux)**	**CCT (K)**
1	**100% clear**	323.1	4721.0	305.4	4510.2
2	**100% blue**	340.9	9602.0	297.1	8970.8
3	**100% bronze**	348.5	2419.0	287.9	2270.2
4	**30% blue**	332.4	5319.5	307.4	5066.6
5	**70% blue**	334.6	6040.0	297.0	5768.6
6	**30% bronze**	333.1	3976.5	301.8	3816.0
7	**70% bronze**	343.0	3462.5	302.0	3269.4

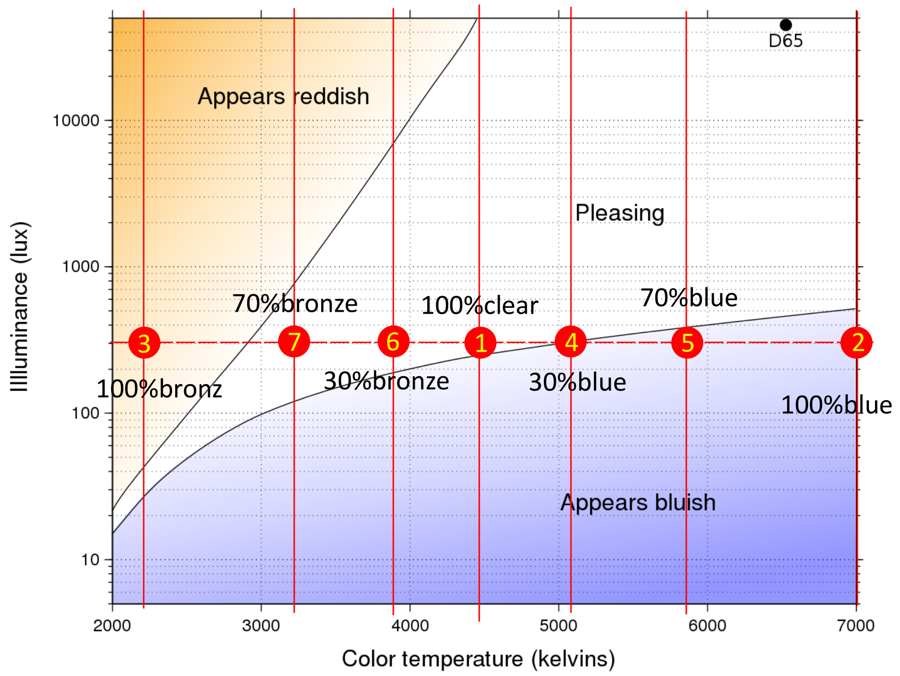
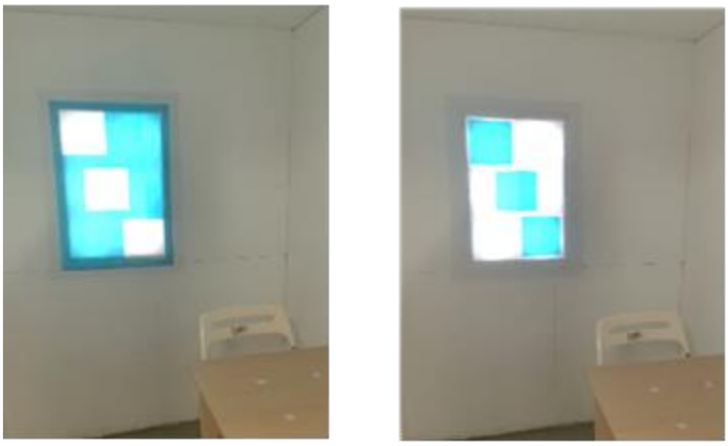


Fig. 5 Kruithof curve with measured CCT.



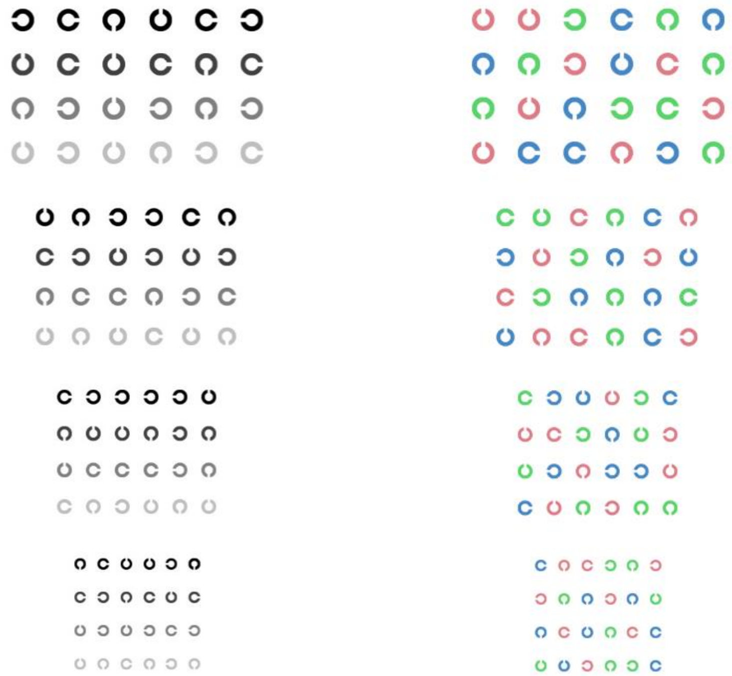
(a) 70%blue (b) 30%blue

Fig. 6 Examples of luminous environment of the developed test room.

2.3. Tasks for evaluating visual performance

In this study, Landolt ring charts were used to measure visual acuity, colour discrimination and completion time of tasks that participants undertook under the various luminous environments. Previous studies indicated that visual tests involving Landolt rings are repeatable and accurate, making them ideal for this study [26, 38]. In a typical Landolt ring chart there are normally 12 rows of rings arranged according to the size of rings, from the maximum at the top (8.0M letter) to the minimum at the bottom (0.63 M letter) [26].

In this study however, the normal Landolt ring charts were modified by removing the first six rows and last two rows of the rings. These rows of rings were deemed too easy or too difficult to be identified for participants in a 1m distance test, such as proposed in this study where the charts were mounted onto the wall opposite the artificial window at 1.2 m from participants. This modification can help the test be more efficient and meaningful. Furthermore, the test involved completion of visual tasks in the form of two types of Landolt rings – achromatic and chromatic rings as shown in Fig. 7. Visual acuity was measured using the achromatic rings (Fig. 7 (a)), and colour discrimination was evaluated using the chromatic rings (Fig. 7 (b)). For the visual acuity test, each row of Landolt ring with similar size were repeated four times, however with contrasting range varying from 0% to 75% brightness. This modification was used to ensure sufficient difficulty for the planed tasks. This resulted in a quantifiable difference between the luminous environments due to the change of the proposed seven window systems at different testing scenarios. The rings with different gap orientation (i.e. up, down, left and right) are randomly distributed on the achromatic and chromatic ring charts in order to avoid unwanted learning effects during the tests. Participants were instructed to fluently read the orientation of each ring from top to the bottom while the answer and completed time were measured using a dictaphone and stopwatch respectively to assess participants' error rate and working speed.



(a) Achromatic ring chart (b) Chromatic ring chart

Fig. 7 Achromatic and chromatic Landolt ring chart used in objective tasks (not to scale)

As for the chromatic ring chart, as shown in Fig.7 (b), a similar arrangement to the achromatic ring chart was used – 4 rows of ring of the same size but with three different colours (i.e. red, green and blue) and constant contrast (i.e. 0% brightness). The three colours of red, green, and blue were used to represent the three main components of the RGB model [38]. The three coloured rings are randomly distributed on the chromatic chart to avoid unwanted learning effects. The spectral reflectance of the three colour rings was measured by an Ocean Optics Spectrometer USB2000+VIS-NIR-ES. Based on the spectral reflectance the chromaticity coordinates of the three coloured rings can be determined and mapped onto a CIE 1931 colour space chromaticity diagram as shown in Fig. 8. The x and y coordinates, respectively, for the rings were: red (0.381, 0.310), green (0.265, 0.405) and blue (0.192, 0.226).

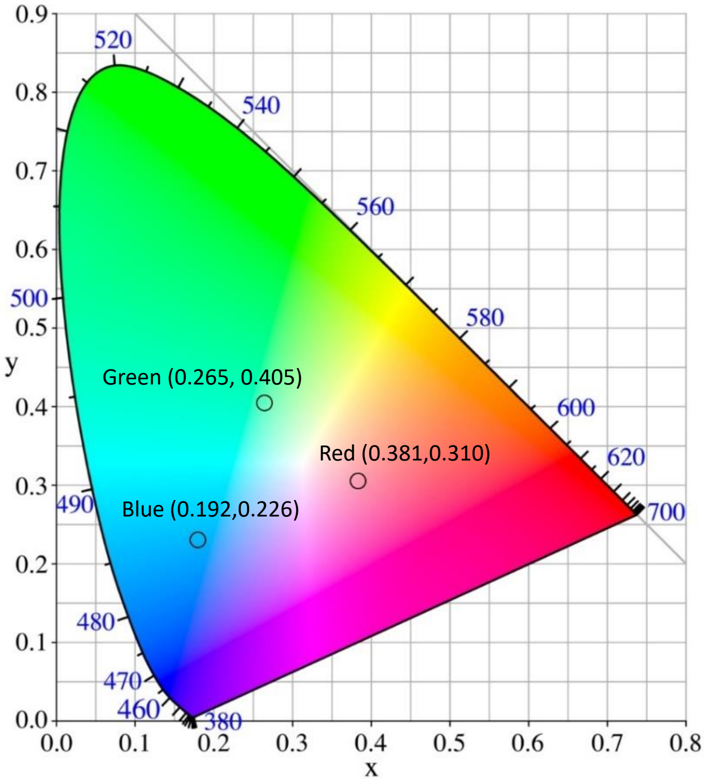


Fig. 8 The chromaticity coordinates of the three rings' colour on the CIE 1931 colour space chromaticity diagram

The luminance of the two charts were measured using a Hagner Universal Photometer Model S3 under all the proposed testing conditions. The target luminance is the luminance measured on the rings on the paper. Luminance of the immediate surroundings of the Landolt rings on the paper was also measured and recorded as background luminance. The contrast (C) of each ring is given by Weber's formula (as shown in Equation 1) [15], where L_t is the target luminance and L_b is the background luminance. The contrast for each ring is then given by Equation (1):

$$C = (L_t - L_b)/L_b \qquad (1)$$

The calculated contrasts for each ring are shown in Table 3. As expected, the results show that under all seven scenarios, contrast for the black rings is gradually reducing with increased brightness from 0% to 75%. For the colored rings, under all scenarios except 100% clear, the contrast of red rings is lower than for green ones, while that of green rings is lower than for blue rings.

Table 3 Contrast of black rings on achromatic ring chart and red, green, blue rings on chromatic ring chart.

No.		Black (0%)	Black (25%)	Black (50%)	Black (75%)	Red	Green	Blue
1	100% clear	-0.86	-0.82	-0.64	-0.34	-0.68	-0.55	-0.62
2	100% blue	-0.85	-0.80	-0.62	-0.29	-0.50	-0.53	-0.59
3	100% bronze	-0.85	-0.81	-0.63	-0.29	-0.38	-0.62	-0.69
4	30% blue	-0.85	-0.80	-0.62	-0.28	-0.46	-0.56	-0.62
5	70% blue	-0.85	-0.80	-0.63	-0.29	-0.45	-0.53	-0.64
6	30% bronze	-0.85	-0.81	-0.63	-0.30	-0.47	-0.54	-0.61
7	70% bronze	-0.85	-0.81	-0.63	-0.31	-0.45	-0.61	-0.67

2.4. Assessment for perception of overall comfort, light level, pleasantness, alertness and the difficulty of objective tasks

During the study, participants were required to fill out three short questionnaires. Questionnaires A and B are required to be completed by participants before the test. Questionnaire A is used to collect general demographic information including age, gender, ethnic background, and visual acuity. Questionnaire B uses the Pittsburgh Sleep Quality Index (PSQI) [39] so that participants can complete a self-assessment of their sleep quality over a one month period. Results show that most of the participants (i.e. 25 participants) have a ‘perfect’ or ‘good’ sleep quality. It can therefore be identified that sleep issues would not have a significant effect on the participants’ performance during the experiment.

Questionnaire C was filled out after completing the two objective tasks and aimed to collect subjective assessments of the luminous environment using a ten-point Likert scale implementing semantic bipolar words. The questionnaire consisted of the 10 questions shown in Table 4, which were designed to assess visual perception in terms of overall comfort, light level, pleasantness, alertness and the difficulty of subjective tasks. These factors can heavily influence a person’s perception of the quality of an indoor luminous environment [18, 26]. An additional question has also been included in questionnaire C as shown in Table 5. It is the Karolinska Sleepiness Scale (KSS) [40] which is used to obtain feedback of participants’ sleepiness under different luminous environments and it has been widely used by other studies to assess subjective sleepiness [18, 41]. Results of this question can be used to assess the alertness of participants.

Table 4 Questionnaire C

Description	No.	Question	Bipolar description	Reference
Overall comfort	Q1	Overall, I find the lighting conditions of this room to be	Very uncomfortable- very comfortable	[18]
	Q2	On a working day, I Predict that I could work under these lighting condition for	<30min, 30-60min, 60-90min, 90-120min, >120min	[26]
	Q3	Do you think this lighting environment is appropriate for office work in?	Unacceptable-acceptable	[26]
Light level	Q4	The lighting distribution in this room is	Uneven - Uniform	[26, 42, 43]
	Q5	I perceive the room as a whole to be	Dark-bright	[26, 43]
Pleasantness	Q6	Under this lighting the overall room appears to be?	Very unpleasant-very pleasant	[14, 18, 42, 44]
Alertness	Q7	The lighting in the room makes me feel	sleepy-alert	[26]
difficulty of subjective tasks	Q8	It was difficult to identify the gap orientation of the rings in the test	Strongly agree-strongly disagree	[26]
	Q9	How easy was it for you to identify the colours of the rings in the test?	Difficult - easy	[26]
	Q10	The contrast of the coloured ring chart was	Low - high	[45-47]

Table 5 Karolinska Sleepiness Scale

Rating	Verbal descriptions
1	Extremely alert

2	Very alert
3	Alert
4	Fairly alert
5	Neither alert nor sleepy
6	Some sings of sleepiness
7	Sleepy, but no effort to keep alert
8	Sleepy, some effort to keep alert
9	Very Sleepy, great effort to keep alert, fighting sleep

2.3. Experimental Procedure

An initial pilot test using 4 participants was conducted to verify the feasibility of the experimental procedure. The University of Nottingham Ethics Committee assessed and approved the experimental procedure and questionnaires applied in this study. For the main experiment, 27 participants were recruited using online advertisements and attended the proposed tests. They are Undergraduate students, Postgraduate students, Researchers and Academics at the University of Nottingham aged between 20 and 32, of which 16 are male and 11 female. None of them reported colour vision problems (e.g. colour blindness) but 13 participants required corrective lenses in the experiment. The experimental procedure and duration are indicated in Table 6. The experiment began with the researcher reading the experimental instruction and explaining the whole procedure for the participant in a waiting area outside of the laboratory. If the participant agreed to continue the rest of the experiment, they were required to sign a consent form and complete Questionnaires A and B. After that, the participant would be taken to the test room and seated at a table during the experiments, wherein the tasks were mounted on the wall at eye level to the participant. The participant was then instructed from outside of the test room by the researcher via vocal commands.

In each luminous environment, the participant was required to complete two tasks, a gap detection task using the achromatic Landolt ring chart and a colour naming task using the chromatic Landolt ring chart. The gap detection task required participants to identify the orientation of the gap in the ring relating to its cardinal direction (i.e. up, down, left, or right). The colour naming task asked participants to recognize the colour of the ring (i.e. red, green, or blue). If participants could not clearly tell the orientation or colour of the rings, they would be encouraged to guess the answer for all the rings on the chart. Both of the two tasks were completed via vocally answering for each ring while a dictaphone and stopwatch were turned on to record the voice and time. Before starting the tasks the participant was instructed to look around the surrounding environment for about 5 minutes for colour adaption of the luminous environment. After hearing the researcher's vocal command 'start', the participant would start one of the two tasks by going through every single Landolt ring from left to right, and top to bottom. Once the first task was completed, the participant would indicate by saying 'finish' and then repeated the same procedure for the second task. After completing the tasks, the participant was asked to fill out Questionnaire C relating to their visual perception for the inside luminous environment. The participant was given 5 minutes to break and relax in normal luminous environment outside the laboratory, whilst the researcher changed the colour films on the artificial window for the next test. The same process was then repeated for the remaining six colour films. During the test, participants have been instructed to sit with back towards the artificial window when immersing into the luminous environment. They are not able to know the types of chromatic patterned glazing, which means the presentation of the patterns of the chromatic glazing would not influence participants' judgement. Unwanted procedure biases of fatigue and learning effect were eliminated by randomly assigning the order of the two tasks for the participants, the order of questions in Questionnaire C and the sequence of the seven luminous environments. The completion time of the whole experiment is approximately 103 minutes.

Table 6 Experiment Procedure

Time	Activity	Minutes
00:00-00:05	The overview of the experimental instruction and procedure	5
00:05-00:06	Sign the consent form	1
00:06-00:07	Complete the Questionnaire A	1
00:07-00:10	Complete the Questionnaire B	3
00:10-00:16	Ask participant to sit down in the test room, observe the environment for at least 2 minutes, and then finish the two objective tests	6
00:16-00:19	Complete Questionnaire C	3

00:19-00:24	Break	5
00:24-01:43	Repeat the same steps for the rest of the colour films 2-7	79
00:00-01:43	Approximate time needed	103

2.4. Statistical analysis

Statistical analysis was carried out on the results of the objective and subjective tests using SPSS Statistics Version 26. For objective tests, the number of errors made by participants of the gap direction on circles and colour of circles was collected from achromatic ring chart testing and chromatic ring chart testing, respectively. In addition, the time needed to complete each test was also collected. For subjective testing, analysis was conducted for participants' response to the questionnaire. Before conducting statistical analysis, assessment on the assumption of data distribution was carried out by using Kolmogorov-Smirnov [48] and Shapiro-Wilks tests [49]. In addition, the variances in the data across independent variables (i.e. window conditions) was assessed using the Levine's test [50]. When the assumptions of normal distribution and homogeneity of variances across data were met (i.e. all $p>0.05$), one-way repeated measures (ANOVA) testing was used for the statistical analysis. Mean values were considered as a reliable indicator of the data distribution, while if either of the assumptions were violated, the median values from the data would be used and the non-parametric Friedman's ANOVA test applied for statistical analysis. Accordingly, the number of errors and duration for each ring chart test were analysed using the non-parametric Friedman's ANOVA, while data collected from questionnaire were analysed using repeated-measures ANOVA test. These tests were used to determine whether the difference detected in objective tests or subjective responses were statistically significant across the seven luminous conditions.

Furthermore, Post Hoc analyses were conducted to compare the significance of any difference between any two groups of data (i.e., using paired comparison to determine which luminous environment was perceived differently from the others). To simplify the pairwise comparisons discussion, the seven luminous environments were divided into two groups including a warm luminous environment group and a cool luminous environment group. The warm luminous environment group consists of 30% bronze, 70% bronze, and 100% bronze, while the cool luminous environment group includes 30% blue, 70% blue and 100% blue. Neutral clear glazing (100% clear) with neutral colour will be classified into both of the two groups. Therefore, the paired comparisons in the warm luminous environment include six comparisons which are 100% bronze vs 70% bronze, 100% bronze vs 30% bronze, 70% bronze vs 30% bronze, 100% bronze vs 100% clear, 70% bronze vs 100% clear and 30% bronze vs 100% clear. And the six paired comparisons in the cool luminous environment group are 100% blue vs 70% blue, 100% blue vs 30% blue, 70% blue vs 30% blue, 100% blue vs 100% clear, 70% blue vs 100% clear and 30% blue vs 100% clear. The pairwise comparisons were carried out for the warm and cool luminous environment group, respectively, while the luminous environment with the best performance in each group were determined. For determining which luminous environment performs best in different aspects, a further pairwise comparison would be conducted between the two selected luminous environments with the best performance. The corresponding Post Hoc analysis for Friedman's ANOVA test and repeated-measures ANOVA test were the Wilcoxon Signed-Rank test and paired sample t-test respectively [51]. To avoid type I error (rejecting the null hypothesis when it is true) when it occurred within multiple comparisons, Bonferroni adjustments for *p*-value (*p* is significant at 0.05 divided by number of paired comparisons) were applied. In addition to the statistical significance values, effect sizes were also reported to provide a standardised measure of the magnitude of the difference and allow for comparisons among similar studies [52] which can be derived from different statistical tests [53]. The effect sizes partial eta squared (η_p^2) and Pearson's *r* were estimated from the inferential tests. Interpretation of the effect sizes was inferred using "small", "moderate", and "large" thresholds recommended by Ferguson [52].

3. Results

3.1. Objective assessment

To measure visual accuracy and colour discrimination objectively, the analysis was conducted for the number of errors collected for achromatic ring chart and chromatic ring chart tests, respectively, under seven luminous environments [54-56]. In addition, time duration for the two tests was also recorded to assess the speed of work for participants under different luminous environments [57]. Errors and times collected from the achromatic ring chart test are denoted by error_a and time_a, while those collected from chromatic ring chart test are denoted as error_c and time_c.

Table 7 shows the results obtained from Friedman's ANOVA test including mean rank, median values

(M_{dn}), inter-quartile range (IQR), test statistic (x^2) and statistical significance (*p*-value) for the performance in Landolt ring chart test under the seven luminous conditions.

Table 7 Friedmen test of error_c, time_c, error_a and time_a in objective test

	Condition	**Mean Rank**	**M_{dn} (IQR)**	**x^2**	***p*-value**
error_c	clear	4.35	6.00 (8)	30.410	0.000*
	blue	2.46	5.00 (7)		
	bronze	5.33	8.00 (9)		
	30%blue	3.46	6.00 (7)		
	70%blue	3.89	6.00 (7)		
	30%bronze	3.83	6.00 (8)		
	70%bronze	4.67	8.00 (11)		
time_c	clear	4.63	89.5 (28.25)	11.467	0.075
	blue	3.56	87.5 (26.5)		
	bronze	4.79	88.5 (33)		
	30%blue	4.02	88 (24.75)		
	70%blue	3.13	86 (25.5)		
	30%bronze	3.79	85 (18.75)		
	70%bronze	4.08	89 (33.75)		
error_a	clear	3.74	0 (1)	5.993	0.424
	blue	3.63	0 (1)		
	bronze	3.74	0 (1)		
	30%blue	4.44	0 (2)		
	70%blue	4.19	0 (1)		
	30%bronze	4.26	0 (1)		
	70%bronze	4	0 (1)		
time_a	clear	3.96	83.5(26.75)	5.361	0.498
	blue	4.15	84(23.25)		
	bronze	3.81	83.5(28.5)		
	30%blue	4.08	85.5(25.75)		
	70%blue	3.35	80.5 (25)		
	30%bronze	3.98	85.5 (29.5)		
	70%bronze	4.67	89 (33.25)		

The results of the Friedman's ANOVA test showed that only error_c was significantly different across the seven conditions $x^2(6) = 30.41$, p<0.01, which indicates that colour discrimination was affected by luminous environments with different CCT. error_a, time_c, and time_a showed non-significant differences which indicates that the accuracy measured by the achromatic chart and time taken by participants to finish the two tests was not influenced by different luminous environments. The time results indicates that luminous environments with different CCT did not significantly impact the participants' working speed [9]. Hence, pairwise comparisons were only conducted for error_c to isolate the main effects between variables using Wilcoxon signed rank with the Bonferroni corrected *p*-value (0.05/21=0.00238).

Table 8 shows the results of the Wilcoxon signed rank pairwise comparison test. The table reports the Median (M_{dn}), IQR, *p*-value, positive and negative ranks, ties, statistic Z score and effect size (*r*). The results indicates that only 5 out of 21 cases were statistically significant (*p*<0.00238) with small effect sizes (0.2<r<0.5). However, effect size for some of the pairwise comparisons were notable, such as 100% bronze vs 30% bronze (r=0.357) and 70% bronze vs 30% bronze (r=0.224). In these cases, the effect size fell into the 'small' range (i.e. 0.2<r<0.5). This implies that these cases may obtain significant results with increasing the sample size [58]. Furthermore, the application of Bonferroni corrections on the statistical significance value may be too strict, which may risk producing Type 2 error [59] (i.e. failure to reject the null hypothesis when it is false) . Therefore, the results with non-significant *p*-value by notable effect size were considered and discussed.

The results of pairwise comparisons carried out for warm luminous environments group indicated a non-significant difference with small effect (0.2<*r*<0.5) between 30% bronze and 70%, and 100% bronze conditions. The effect sizes, along with the medians, indicate that the errors were slightly lower for the 30% bronze condition (i.e., participants performed slightly better under 30% bronze in colour discrimination tests). The comparison between the 30% bronze and 100% clear showed no statistically significant difference was seen with negligible magnitude (*r*<0.2). It can be inferred that participants performed best under 30% bronze in the warm luminous environment group. However, no statistical difference was found between 30% bronze and 100% clear. For the cool luminous environment group, non-significant difference but small effect size (0.2<*r*<0.5) were detected for 100% blue vs 70% blue and 100% blue vs 30% blue. The lower medians of error_c for 100% blue indicate that less errors were made under 100% blue when compare with 70% blue and 30% blue, providing evidence that 100% blue performs slightly better in colour discrimination than the other two conditions. In addition, significantly different from null hypothesis ($p<0.00238$) was detected for 100% blue vs 100% clear. The comparison of median values within the comparison shows that the errors were less for 100% blue, which means the performance of 100% blue in colour discrimination is significantly better than that of 100% clear. Since 30% bronze and 100% blue perform the best among the warm and cool luminous environment group respectively, a comparison between them was conducted. Although non-statistically significant difference was detected, a 'small' effect size was found in the comparison of 30% bronze and 100 % blue. The median value of the 30% bronze (Mdn=6) is higher than that of 100 % blue (Mdn=5), with a higher number of positive rank. Thus, it can be indicated that 100% blue has better colour discrimination performance than 30% bronze. Additionally, it can be inferred that participants performed the best in colour discrimination under the 100 % CAR when compared with the remaining six luminous environments. This provides evidence that people can more clearly tell the difference between similar colours (especially blue and green) under 100% blue condition which is of the highest CCT.

In summary, the ranking of the performance in colour discrimination for the seven luminous environments can be estimated to be 100% blue > 30% bronze = 70% blue = 30% blue = 100% clear > 70% bronze > 100% bronze ('>' means the better performance, '=' means similar performance). The ranking indicated that 100% blue has the best performance, followed by four luminous environments with similar performance that include 30% bronze, 70% blue, 30% blue and 100% clear. All the four luminous environments perform slightly better than 70% bronze, while 100% bronze was assumed to perform the worse in colour discrimination among the seven luminous environments.

Table 8 Pairwise comparison results of Wilcoxon signed rank test for error_c

Paired comparison	Mdn(IQR)	Mdn(IQR)	p-value	Negative	Positive	Ties	z_score	effective size r
100% bronze vs 70% bronze	8(9)	8(11)	0.316	115	185	3	-1.002	0.136
100% bronze vs 30% bronze	8(9)	6(8)	0.009	52	224	4	-2.623	0.357*
70% bronze vs 30% bronze	8(11)	6(8)	0.1	101.5	223.5	2	-1.645	0.224*
100% bronze vs 100% clear	8(9)	6(8)	0.047	80.5	219.5	3	-1.989	0.271*
70% bronze vs 100% clear	8(11)	6(8)	0.483	148	203	1	-0.702	0.096

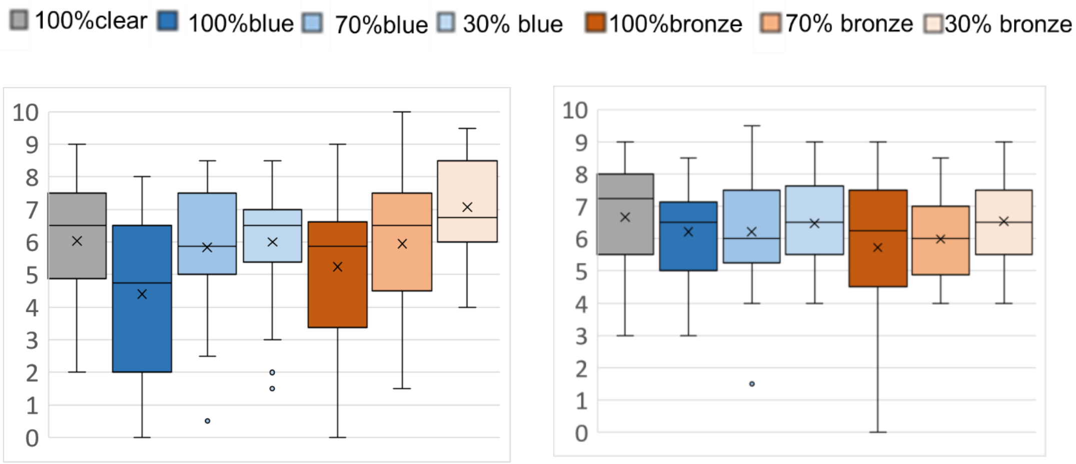
30% bronze vs 100% clear	6(8)	6(8)	0.233	177	99	4	-1.194	0.162
100% blue vs 70% blue	5(7)	6(7)	0.062	231.5	93.5	2	-1.869	0.254*
100% blue vs 30% blue	5(7)	6(7)	0.092	241.5	109.5	1	-1.683	0.229*
70% blue vs 30% blue	6(7)	6(7)	0.49	137	188	2	-0.69	0.094
100% blue vs 100% clear	5(7)	6(8)	0.001*	287.5	37.5	2	-3.392	0.462*
70% blue vs 100% clear	6(7)	6(8)	0.234	177	99	4	-1.191	0.162
30% blue vs 100% clear	6(7(	6(8)	0.16	199	101	3	-1.406	0.191
100% bronze vs 100% blue	8(9)	5(7)	0.000**	12	313	2	-4.056	0.552**
70% bronze vs 100% blue	8(11)	5(7)	0.002*	34	242	4	-3.17	0.431*
30% bronze vs 100% blue	6(8)	5(7)	0.051	74	202	1	-1.953	0.266*
70% blue vs 100% bronze	6(11)	8(9)	0.001*	311	40	1	-3.458	0.471*
30% blue vs 100% bronze	6(7)	8(9)	0.002*	258.5	41.5	3	-3.116	0.424*
70% bronze vs 70% blue	8(11)	6(7)	0.053	109	269	0	-1.931	0.263*
70% bronze vs 30% blue	8(11)	6(7)	0.035	84.5	240.5	2	-2.107	0.287*
30% bronze vs 70% blue	6(8)	6(7)	0.584	169	131	3	-0.548	0.075
30% bronze vs 30% blue	6(8)	6(7)	0.598	143	182	2	-0.527	0.072

$r < 0.20$ = negligible; $0.20 \le r < 0.50$ = small; $0.50 \le r < 0.80$ = moderate; $r \ge 0.80$ = large.

p-value: ** statistically significant at the 0.01 level (2-tailed), * statistically significant at the 0.05 level (2-tailed). Effect size: ***Large, **Moderate, *Small.

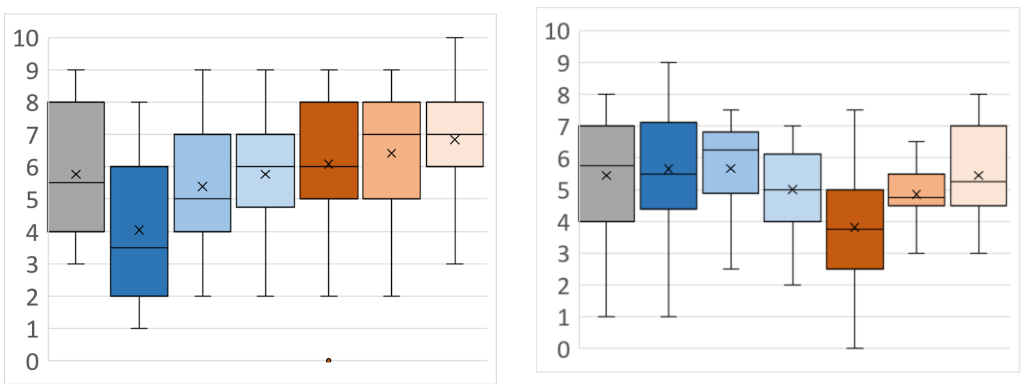
3.2. Subjective assessment

After finishing the objective tests, the visual perception in terms of overall comfort, light level, pleasantness, alertness, difficulty rating for achromatic ring chart tests and chromatic ring chart tests were assessed by subjective rating using 12 questions. Fig. 9 (a-f) presents the results collected from the 12 questionnaires. Each plot shows the results of one parameter of visual perception which are overall comfort, light level, pleasantness, alertness, the ease level for participants to finish achromatic ring chart testing and chromatic ring chart testing respectively. The y-axis in each plot presents the subjective rating from 0 to 10 by participants under the seven luminous environments, with 0 representing ‘not at all’ and 10 meaning ‘very much’. The seven colours represent the seven luminous environments as indicated in the legend on Figure 6. It was found that there were obvious variations of the subjective rating in Fig. 9 (a), (c), (d) and (f) across the seven luminous environments. In Fig. 9 (a) and (c), when participants were asked to assess the overall comfort and pleasantness under different conditions, the luminous environment of the warm group (i.e. 100% bronze, 70% bronze and 30% bronze) seems to have higher ratings than the cool group (i.e. 100% blue, 70% blue and 30% blue). In addition, it seems the luminous environment with less percentage of chromatic glazing area has more potential to obtain a high rating (i.e. 30% bronze > 70% bronze > 100% bronze; 30% blue> 70% blue> 100% blue). However, in terms of alertness and ease of chromatic ring chart testing, as shown in Figure 9 (d) and (f), the luminous environment of the cool group may will be rating higher than that of warm group.



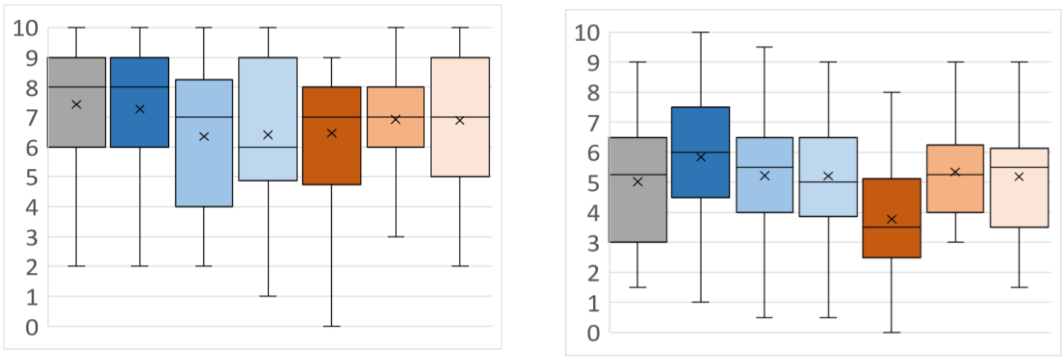
(a) overall comfort

(b) light level



(c) pleasantness

(d) alertness



(e) difficulty of achromatic ring chart test (f) difficulty of chromatic ring chart test

Fig. 9. Boxplots of factors of visual perception under seven luminous environments. Note: the cross indicates the mean vale

Repeated-measures ANOVA testing was applied for detecting statistically significant differences across the seven luminous environments. The F test statistic, degree of freedom (df), statistical significance (p-value) and effect size (η_p^2) were reported as shown in Table 9. The ANOVA test results show that 4 out of 6 factors (i.e overall comfort, pleasantness, alertness and ease level of chromatic ring chart testing) detected statistically significant differences across the seven luminous environments. All of these four factors showed highly significant difference (i.e. $p<0.001$) among the seven luminous environments. In addition, large effect size was detected ($0.64< \eta_p^2 \leq 0.8$) for overall comfort and alertness, while moderate effect size was detected ($0.25< \eta_p^2 \leq 0.64$) for pleasantness and ease level of chromatic ring chart testing. The analysis of the test results suggested that the change of luminous environment has a substantial effect on most of the factors of visual perception.

Table 9 Results of repeated measurement ANOVA test for each factor of visual perception

Factor of visual perception	**F**	**df**	**p-value**	**Effect size (η_p^2)**
Overall comfort	7.2	6	0.000*	0.684*
Light level	1.920	4.479	0.104	0.071
Pleasantness	5.957	6	0.001*	0.641*
Alertness	6.751	6	0.001*	0.669*
Ease level of achromatic ring chart test	2.02	6	0.066	0.075

Ease level of chromatic ring chart test	4.646	4.697	0.001*	0.157*

η_p^2<0.04 = negligible; η_p^2≥0.04 = small; η_p^2≥0.25 = moderate; η_p^2≥0.64 = large.

3.2.1. Analysis for overall comfort

For isolating the relevant differences in the analyses found in Table 9, and figuring out which luminous environment had the most positive influence on these factors of visual perception, pairwise comparisons were carried out using the dependent t-test. Table 10 shows the comparison results of repeated-measures ANOVA test for overall comfort. The tables report Mean value, test statistic (t), statistical significance (p-value) and the effect size (r). For the overall comfort participants perceived under a warm luminous environment, the comparisons 100% bronze vs 30% bronze were found to have statistical significance (i.e. $p<0.00238$) and their effect size (r) fell into the 'moderate' range. The comparison 70% bronze vs 30% bronze was also found to have substantial effect size (r) falling into the 'small' range. Comparison of their mean values shows that 30% bronze (mean=7.08) is higher than 100% bronze (mean=5.24) and 70% bronze (mean=5.94). This means 30% bronze performs best in overall comfort among the warm luminous environments. When compared with 100% clear, the subjective rating of 30% bronze (mean =7.08) is also statistically significant higher than 100% clear (mean=6.04) with notable effect size (r=0.4). The results of pairwise comparisons among the cool luminous environment group indicated that non statistical significant difference can be detected in any paired comparison, but 'small' effect size was found in the comparison of 100% blue vs 70% blue and 100% blue vs 30% blue. The mean rating for 100% blue (mean=4.4) is lower than that of 70% blue (mean=5.84) and 30% blue (mean=6), while no statistical significant difference and no notable effect size were found in the comparison between 70% blue and 30% blue. This indicated that both 30% blue and 70% blue perform better that 100% blue. However, the comparison results of 70% blue vs 100% clear and 30% blue vs 100% clear indicated that there was no significant difference detected from null hypothesis ($p< 0.00238$). For further determining which luminous environment performs best among the seven conditions, the results of 30% bronze vs 30% blue and 30% bronze vs 70% blue were compared. Although there is no statistical significant differences found in the two comparisons, the substantial effect size (r) was detected. And mean value of 30% bronze (mean=7.08) is higher than that of 30% blue (mean=6) and 70% blue (mean=5.84). Therefore, it can be concluded that 30% bronze performs best in overall comfort when compared with the other six luminous environments, which means that participants gave the highest rating of 30% bronze in terms of overall comfort.

In summary, participants perceived overall comfort for the seven luminous environments is ranked as: 30% bronze > 30% blue = 70% blue = 70% bronze = 100% clear > 100% bronze = 100% blue, where participants perceived the best overall comfort under 30% bronze and felt 30% blue, 70% blue, 70% bronze and 100% clear to have a similar effect on overall comfort, however, these luminous environments all performed slightly better than 100% bronze and 100% blue.

Table 10 Pairwise comparison results of depend t test for overall comfort

Paired comparison	Mean 1	Mean 2	t(df=25)	p-value	effect size (r)
100% bronze vs 70% bronze	5.24	5.94	-1.48	0.151	0.201*
100% bronze vs 30% bronze	5.24	7.08	-5.017	0.000**	0.683**
70% bronze vs 30% bronze	5.94	7.08	-3.019	0.006	0.411*
100% bronze vs 100% clear	5.24	6.04	-1.63	0.116	0.222*
70% bronze vs 100% clear	5.94	6.04	-0.197	0.846	0.027
30% bronze vs 100% clear	7.08	6.04	2.942	0.007	0.400*
100% blue vs 70% blue	4.4	5.84	-2.816	0.009	0.383*
100% blue vs 30% blue	4.4	6	-3.112	0.005	0.423*
70% blue vs 30% blue	5.84	6	-0.423	0.676	0.058
100% blue vs 100% clear	4.4	6.04	-2.854	0.009	0.388*
70% blue vs 100% clear	5.84	6.04	-0.46	0.65	0.063
30% blue vs 100% clear	6	6.04	-0.082	0.936	0.011
100% bronze vs 100% blue	6.04	5.24	1.385	0.178	0.188
70% bronze vs 100% blue	5.94	4.40	2.324	0.029	0.316*
30% bronze vs 100% blue	7.08	4.40	4.919	0.000**	0.669**
70% blue vs 100% bronze	5.84	5.24	1.341	0.192	0.182
30% blue vs 100% bronze	6.00	5.24	1.332	0.195	0.181
70% bronze vs 70% blue	5.94	5.84	0.195	0.847	0.027

70% bronze vs 30% blue	5.94	6.00	-0.127	0.9	0.017
30% bronze vs 70% blue	7.08	5.84	2.981	0.006	0.406*
30% bronze vs 30% blue	7.08	6.00	2.301	0.03	0.313*

r < 0.20 = negligible; 0.20 ≤ *r* < 0.50 = small; 0.50 ≤ *r* < 0.80 = moderate; *r* ≥ 0.80 = large.

p-value: ** statistically significant at the 0.01 level (2-tailed), * statistically significant at the 0.05 level (2-tailed). Effect size: ***Large, **Moderate, *Small.

3.2.2. Analysis for pleasantness

Pairwise comparison results in terms of pleasantness are shown in Table 11. None of the cases were found to be statistically significant (p<0.00238) within the warm luminous environment group. Only 1 out of 3 cases which is 100% bronze vs 30% bronze presented differences based in their effect size (i.e. falling into the small range 0.2<r<0.5). The mean value of 30% bronze has a higher rating than that of 100% bronze. This result indicated that 30% bronze may lead to relatively greater pleasantness than the other two warm luminous environments (i.e. 100% bronze and 70% bronze). In addition, the pairwise comparison of 30% bronze and 100% clear show significant difference in their effect size (r=0.403) falling into 'small' range. The comparison of 30% bronze (Mean=6.85) and 100% clear (Mean=5.77) indicated that 30% bronze performed better than the 100% clear. Regarding the results of pairwise comparison within the cool luminous environment group, only 100% blue vs 30% blue have detected statistical significant difference (p<0.00238), with effect size falling into the 'moderate' range. It can also be seen that the effect size (r) for the comparison of 100% blue and 70% blue falls into the 'small' range.

In addition, the mean rating of 100% blue is lower than that of 30% blue and 70% blue. This means participants perceive 30% blue and 70% blue to be more pleasant than 100% blue. However, there is no statistical differences found in the paired comparison of 100% clear vs 30% blue and 100% clear vs 70% blue, which means the performance of 30% blue, 70% blue and 100% clear in terms of pleasantness are the same. To further explore which luminous environment performed best in terms of pleasantness, the comparisons 30% bronze vs 30% blue and 30% bronze vs 70% blue were carried out. Significant differences (p<0.00238) with 'moderate' effect size for 30% bronze vs 70% blue was detected. As for 30% bronze vs 30% blue, non-significant differences but 'small' effect size was detected. Furthermore, the mean value of 30% bronze (Mean=6.85) is higher than that of 30% blue and 70% blue. Therefore, it can be indicated that 30% bronze is the luminous environment that participants perceive the most pleasant when compared with the other six luminous environments. According to the analysis, the effect of the seven luminous environments on pleasantness from high to low ranks as follow: 30% bronze > 30% blue = 70% blue =70% bronze =100% bronze = 100% clear > 100% blue. It can clearly be seen that the ranking for pleasantness highly corresponds with that of overall comfort, aside from 100% bronze which has been perceived to perform better in pleasantness than that of 100 % blue.

Table 11 Pairwise comparison results of depend t test for pleasantness

Paired comparison	Mean 1	Mean 2	t(df=25)	p-value	effect size (r)
100% bronze vs 70% bronze	6.08	6.42	-0.662	0.514	0.090
100% bronze vs 30% bronze	6.08	6.85	-1.832	0.079	0.249*
70% bronze vs 30% bronze	6.42	6.85	-1.366	0.184	0.186
100% bronze vs 100% clear	6.08	5.77	0.613	0.545	0.083
70% bronze vs 100% clear	6.42	5.77	1.452	0.159	0.198
30% bronze vs 100% clear	6.85	5.77	2.963	0.007	0.403*
100% blue vs 70% blue	4.04	5.38	-3.304	0.003	0.450*
100% blue vs 30% blue	4.04	5.77	-5.025	0.000**	0.684**
70% blue vs 30% blue	5.38	5.77	-1.044	0.306	0.142
100% blue vs 100% clear	4.04	5.77	-3.373	0.002*	0.459*
70% blue vs 100% clear	5.38	5.77	-0.887	0.383	0.121
30% blue vs 100% clear	5.77	5.77	0	1	0.000
100% bronze vs 100% blue	6.08	4.04	3.496	0.002*	0.476*
70% bronze vs 100% blue	6.42	4.04	4.135	0.000**	0.563**
30% bronze vs 100% blue	6.85	4.04	5.036	0.000**	0.685**
70% blue vs 100% bronze	5.38	6.08	-1.614	0.119	0.220*
30% blue vs 100% bronze	5.38	6.08	-0.55	0.587	0.075
70% bronze vs 70% blue	6.42	5.38	2.314	0.029	0.315*

70% bronze vs 30% blue	6.42	5.77	1.486	0.15	0.202*
30% bronze vs 70% blue	6.85	5.38	4.439	0.000**	0.604**
30% bronze vs 30% blue	6.85	5.77	2.409	0.024	0.328*

$r < 0.20$ = negligible; $0.20 \leq r < 0.50$ = small; $0.50 \leq r < 0.80$ = moderate; $r \geq 0.80$ = large.

p-value: ** statistically significant at the 0.01 level (2-tailed), * statistically significant at the 0.05 level (2-tailed). Effect size: ***Large, **Moderate, *Small.

3.2.3. Analysis for alertness

Results in Table 12 explain the perception of alertness. From the results of the comparison within the warm luminous environment group, 100% bronze vs 30% bronze show statistically significant ($p<0.00238$) differences across the seven luminous environments, with the effect sizes falling into the moderate range. 100% bronze vs 70% bronze and 70% bronze vs 30% bronze failed to achieve the required significance. However, their effect size indicated a notable difference as well. According to the median values, the inferential correlations are: 30% bronze > 70% bronze > 100% bronze, where '>' means that the former luminous environment had a higher mean value. This indicates that 30% bronze was the best performer in terms of alertness among the warm luminous environment group. The comparison results of 30% bronze and 100% clear shows no significant differences were found between them. For comparison, results from the cool luminous environment group showed small effect size ($r=0.251$; $r=0.344$) but non-significant difference ($p>0.00238$) for the comparison of 100% blue vs 30% blue and 70% blue vs 30% blue. The mean value of 100% blue and 70% blue were both higher than that of 30% blue. However, neither significant difference nor notable effect size were detected when using 100% clear as compared with 100% blue, 70% blue and 30% blue, respectively. This result indicated that the performance of 100% blue, 70% blue and 30% blue are similar in alertness. For determining which luminous environment performs the best, 30% bronze was compared with 100% blue, 70% blue and 30% blue respectively. However, results indicated that no significant difference can be found in either of the comparisons, which means there is no difference among the 100% blue, 70% blue, 30% blue and 30% bronze in terms of alertness.

The ranking of the seven luminous environments in terms of alertness can be estimated:

100% blue = 70% blue = 30% bronze = 30% blue = 100% clear > 70% bronze > 100% bronze. It shows that participants perceived that they could be more alert under 100% blue, 70% blue, 30% blue, 30% bronze and 100% clear than 70% bronze and 100% bronze, while 70% bronze was slightly better than 100% bronze.

Table 12 Pairwise comparison results of depend t test for alertness

Paired comparison	**Mean 1**	**Mean 2**	**t(df=25)**	**p-value**	**effect size (r)**
100% bronze vs 70% bronze	3.808	4.846	-3.1	0.005	0.422*
100% bronze vs 30% bronze	3.808	5.442	-4.411	0.000**	0.600* *
70% bronze vs 30% bronze	4.846	5.442	-2.898	0.008	0.394*
100% bronze vs 100% clear	3.808	5.442	-4.111	0.000**	0.559**
70% bronze vs 100% clear	4.846	5.442	-1.639	0.114	0.223*
30% bronze vs 100% clear	5.442	5.442	0	1.000	0.000
100% blue vs 70% blue	5.654	5.6635	-0.024	0.981	0.003
100% blue vs 30% blue	5.654	5	1.842	0.077	0.251*
70% blue vs 30% blue	5.6635	5	2.525	0.018	0.344*
100% blue vs 100% clear	5.654	5.442	0.542	0.593	0.074
70% blue vs 100% clear	5.6635	5.442	0.64	0.528	0.087
30% blue vs 100% clear	5	5.442	-1.436	0.163	0.195
100% bronze vs 100% blue	3.808	5.654	-3.958	0.001*	0.539**
70% bronze vs 100% blue	4.846	5.654	-1.945	0.063	0.265*
30% bronze vs 100% blue	5.442	5.654	-0.454	0.654	0.062
70% blue vs 100% bronze	5.6635	3.808	6.378	0.000**	0.868***
30% blue vs 100% bronze	5	3.808	4.386	0.000**	0.597**
70% bronze vs 70% blue	4.846	5.6635	-2.824	0.009	0.384*
70% bronze vs 30% blue	4.846	5	-0.522	0.606	0.071
30% bronze vs 70% blue	5.442	5.6635	-0.72	0.478	0.098
30% bronze vs 30% blue	5.442	5	1.194	0.244	0.162

$r < 0.20$ = negligible; $0.20 \leq r < 0.50$ = small; $0.50 \leq r < 0.80$ = moderate; $r \geq 0.80$ = large.

p-value: ** statistically significant at the 0.01 level (2-tailed), * statistically significant at the 0.05 level

(2-tailed). Effect size: ***Large, **Moderate, *Small.

Mean ratings of the seven luminous environments on the valance/arousal Circumplex model of affect are shown in Fig. 10. Seven luminous environments were represented by seven different colour dots whose location indicated their respective change in perceived affects. The seven dots were distributed at different locations, while the dot for 100% blue in the model reported more arousal but low pleasure, on the contrary, the dots for 100% bronze and 70% bronze showed low arousal and high pleasure. The dots for other luminous environments were mostly in the region of perceived high arousal and high pleasure. The location for 100% blue suggests there was a distressing affect. And participants under 100% bronze and 70% bronze seemed to feel more relaxed. As for 70% blue, 30% blue, 30% bronze and 100% clear, the mean ratings of them in terms of arousal/ valance shifted towards the exciting which is a stimulation affect.

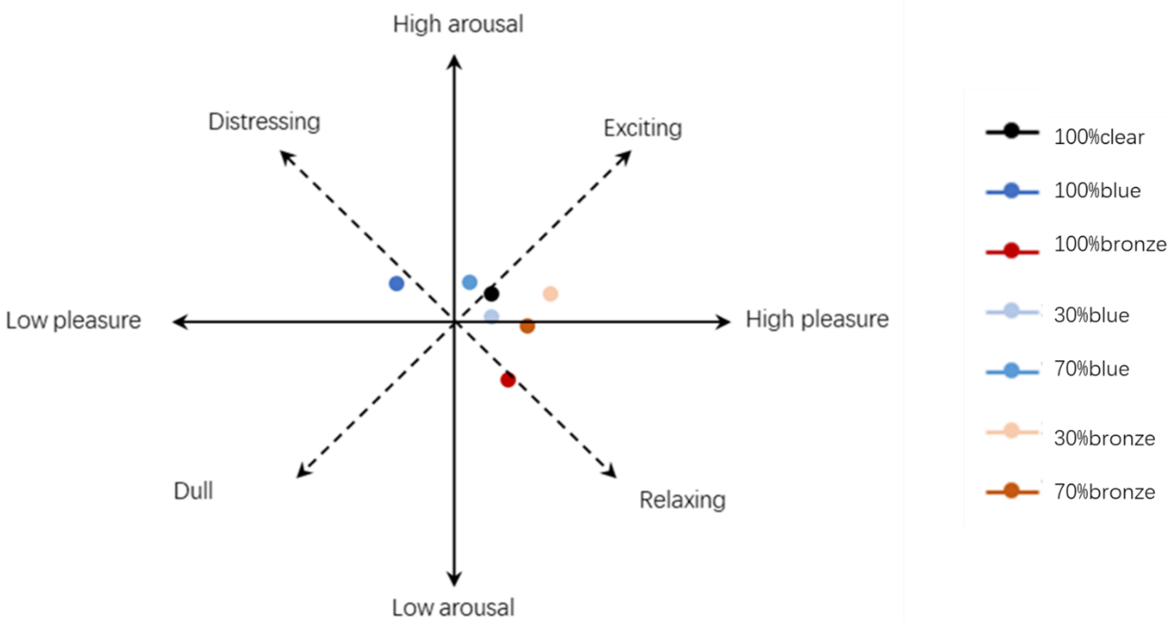


Fig. 10. Mean ratings of view perceived valance/arousal on the Circumplex model of affects

3.2.4. Analysis for rating of difficultly for chromatic ring chart tests

Rating of difficultly for chromatic ring chart tests under the seven different luminous environments was also assessed. The paired comparison results are shown in table 13. Comparisons were firstly carried out within the warm luminous environment group. Only the comparison 100% bronze vs 70% bronze was detected to exhibit a statistically significant difference ($p<0.00238$) from null hypothesis. In addition, notable effect size was also detected for the comparison between 100% bronze and 30% bronze. Comparison of the mean value of 100% bronze (mean=3.769), 70% bronze (mean=5.346) and 30% bronze (mean=5.192) indicated that participants found they could easier finish the chromatic ring chart test under 70% bronze and 30% bronze as compared with 100% bronze. However, no significant difference was detected among 100% clear, 70% bronze and 30% bronze. For the paired comparison results of the cool luminous environment group, it was reported that no statistically significant cases were found, except, a 'small' effect size ($r=0.269$) detected for the comparison of 100% blue and 100% clear. However, 100% blue has been perceived the same as 70% blue and 30% blue, while no difference can be found among 100% clear, 70% blue and 30% blue. Therefore, it can be inferred that 100% blue, 70% blue, 30% blue and 100% clear have the same effect on difficulty rating of a task. The above discussion only helps to determine that the performance of 100% bronze is significantly lower than that of 70% bronze, 30% bronze, 100% blue, 70% blue and 30% blue. For further confirmation, the results of paired comparisons within 70% bronze, 30% bronze, 100% blue, 70% blue and 30% blue were discussed. But for neither of the cases were any significant differences nor notable effect sizes detected. This result indicated that participants perceived there to be no difference for them to finish the chromatic ring chart test under luminous environment 70% bronze, 30% bronze, 100% blue, 70% blue and 30% blue. However, it was harder for them to finish the test under 100% bronze.

Accordingly, the ranking of the seven luminous environments for task difficultly for the chromatic ring chart test can be inferred:

100% blue = 70% blue = 30% blue = 70% bronze = 30% bronze = 100% clear > 100% bronze. The ranking indicated that participants only perceived difficulty in finishing the chromatic ring chart test under 100% bronze as compared with the other conditions.

Table 13 Pairwise comparison results of depend t test for ease level of chromatic ring chart test

Paired comparison	Mean 1	Mean 2	t(df=25)	p-value	effect size (r)
100% bronze vs 70% bronze	3.769	5.346	-5.112	0.000**	0.696**
100% bronze vs 30% bronze	3.769	5.192	-3.124	0.004	0.425*

70% bronze vs 30% bronze	5.346	5.192	0.367	0.717	0.050
100% bronze vs 100% clear	3.769	5.019	-2.742	0.011	0.373*
70% bronze vs 100% clear	5.346	5.019	0.781	0.442	0.106
30% bronze vs 100% clear	5.192	5.019	0.535	0.597	0.073
100% blue vs 70% blue	5.846	5.221	1.222	0.233	0.166
100% blue vs 30% blue	5.846	5.212	1.333	0.194	0.181
70% blue vs 30% blue	5.221	5.212	0.023	0.982	0.003
100% blue vs 100% clear	5.846	5.019	1.979	0.059	0.269*
70% blue vs 100% clear	5.221	5.019	0.531	0.600	0.072
30% blue vs 100% clear	5.212	5.019	0.456	0.652	0.062
100% bronze vs 100% blue	3.769	5.846	-4.290	0.000**	0.584**
70% bronze vs 100% blue	5.346	5.846	-1.011	0.322	0.138
30% bronze vs 100% blue	5.192	5.846	-1.628	0.116	0.222*
70% blue vs 100% bronze	5.221	3.769	3.643	0.001*	0.496*
30% blue vs 100% bronze	5.212	3.769	3.594	0.001*	0.489*
70% bronze vs 70% blue	5.346	5.221	0.327	0.747	0.044
70% bronze vs 30% blue	5.346	5.212	0.371	0.714	0.050
30% bronze vs 70% blue	5.192	5.221	-0.073	0.942	0.010
30% bronze vs 30% blue	5.192	5.212	-0.051	0.959	0.007

$r < 0.20$ = negligible; $0.20 \le r < 0.50$ = small; $0.50 \le r < 0.80$ = moderate; $r \ge 0.80$ = large.

p-value: ** statistically significant at the 0.01 level (2-tailed), * statistically significant at the 0.05 level (2-tailed). Effect size: ***Large, **Moderate, *Small.

4. Discussion

For exploring which luminous environment could perform best in terms of visual accuracy, colour discrimination, working speed and visual perception, the effects of seven designed luminous environments on these factors has been investigated. A comprehensive measurement was carried out to obtain the colorimetric characteristics of the designed test environment, including the artificial window (light source), surrounding environment (walls) and also the task area. Then the effect of the luminous environment on participants was tested when these participants were completely immersed in the environment.

The experimental results indicate that participants' performance in colour discrimination and their visual perception for overall comfort, alertness, pleasantness and difficulty rating of the chromatic ring chart test can be affected by a luminous environment with different chromatic properties as significant difference was detected in these aspects. For other factors including visual accuracy, working speed, light level and rating of difficulty for an achromatic ring chart test, different luminous environments did not show significant statistical differences. Further analysis indicated that under 100% blue participants' results showed the best performance in colour discrimination and alertness while performing worst in overall visual comfort and pleasantness. 100% bronze may perform better than 100% blue in visual comfort and pleasantness, however, it was rated worst in colour discrimination and alertness. These findings may imply that chromatic glazing with a single colour (i.e. bronze and blue) can satisfy only one of the two desired demands: occupants' preference or high working efficiency, which agrees with conclusions made from previous studies. However, the chromatic patterned glazing including 30% bronze, 30% blue, and 70% blue have been given good ratings in all of the aspects. Therefore, it may be possible to infer that chromic patterned glazing, which combines the effects of two chromatic glazing, was able to improve feelings of visual comfort, whilst retaining the efficiency of task completion. A detail discussion for each factor is given in the following sections.

4.1. Discussion on visual accuracy, colour discrimination and working speed

Visual accuracy was evaluated by accounting for error_a in the achromatic ring chart test. Results of the test indicated that there was no significant difference for error_a across the seven luminous environments, meaning visual accuracy was not influenced by the light source with different CCT (i.e. from 2700K to 9600K). This result supported the conclusions from Fotios's and Boyce's studies [56, 57], which stated that a light source with different light spectrum (i.e. different CCT) did not affect participant's performance on achromatic acuity tasks. However, most of the previous research disagreed with this conclusion and found that at the same photopic level a light source with higher CCT would produce better visual accuracy when compared with a light source with lower CCT [60-63]. Because, it has been proven that under a high CCT light source the brightness perception of observers would be improved [64, 65] and their pupil size would reduce, which may enhance visual acuity [60, 66]. In our achromatic ring chart test the mean value of error_a for the seven luminous environments ranged from 0.44 to 1, meaning participants hardly made any mistakes for all the environments (with a total of 96 rings in one chart). One possible reason to explain why the participant's visual acuity cannot be affected by different luminous environments is the design of the achromatic ring chart test is too simple. The test was not challenging enough to hinder completion of the test for most participants, even though luminous environments were changed. Another possible reason may be that the tested light sources were not sufficiently stimulating enough to affect participants' pupil size [67]. As a result, statistically significant difference of visual accuracy cannot be detected across the seven luminous environments. In a previous study [60], differences in light spectrum were also not found to have a statistically significant effect on visual accuracy. Similarly, the authors suspected that the experiment conditions were not extreme enough given the change in participants' pupil area were in the range of 12% to 15%, much smaller than in another study [63] (i.e. 40%).

The performance of colour discrimination of the seven luminous environments was evaluated by measuring the accuracy of colour naming for blue, green and red in the chromatic ring chart test [55]. Significant difference of colour discrimination was detected for the seven luminous environments. The ranking of colour discrimination for the seven luminous environments (i.e. 100% blue > 30% bronze = 70% blue = 30% blue = 100% clear > 70% bronze > 100% bronze) shows that participants had a better ability to discriminate colours in a light environment with high CCT when compared to low CCT. This result agrees with previous studies whose results suggest that the higher the light source's colour temperature the greater the colour discrimination capacity [68-70]. Pardo et al. [71] proposed that a high CCT light source with spectral peak in the zone of more short wavelengths may stimulate and increase the absolute level of excitation of S cones. S cones are photoreceptor cells in the retina of the human eye which mostly contribute to chromatic vision [72]. Therefore, it can be inferred that participants colour discrimination could perform better under a higher CCT light source due to the excitation of S cones. However, further research is required to prove this. In addition, results showed that most of the participants easily confused blue with green or green with blue, especially at the small ring size. This finding has also been reported in previous studies [55, 73] and explained due to the fairly similar spectral reflectance of the blue and green which may result in the two colours being easily confused under the impact of different luminous environments. It is defined by the International Commission on Illumination (CIE) Technical Committee (TC) TC1-91 [74, 75] that colour discrimination is one of the attributes of colour quality of light, and can be evaluated with colour quality metrics. The widely used colour quality metrics Colour Rendering Index (CRI) and Colour Gamut Area (GAI) for the light sources of the seven luminous environments were calculated and provided in Appendix A. Comparing with the experimental results, it was found the metrics GAI can give accurate predictions for colour discrimination of lights, which agrees with the findings from Rea and Freyssinier-Nova's study [76].

The time duration of the two tests was also recorded to assess participants working speed under different luminous environments. In this study working speed was used to indicate the working efficiency under certain conditions [55]. Results from the research stated that participants working speed did not show any significant difference across the seven luminous environments for either of the two tasks. These results are consistent with previous research [57]. Therefore, it can be inferred that working efficiency is not significantly affected by a light source with different CCT. However, other studies disagree with this conclusion and believe that a high CCT environment is beneficial for enhancing work efficiency [61, 77]. The possible reasons to explain the failure of finding any effect of CCT on working speed may be the same as those given for visual accuracy as explained in the previous section.

4.2. Discussion on overall comfort, pleasantness, light level, alertness and difficulty rating for achromatic ring chart test and chromatic ring chart test

For overall comfort and pleasantness, participants gave the highest mark to 30% bronze. A lot of previous research has aimed to investigate the effect of different chromatic glazing on human's visual perception in terms of overall comfort and pleasantness finding that most occupants prefer warm shifts in luminous environment when compared with cool shifts in luminous environments [12, 15, 61, 78]. However, most of these studies have used just one warm luminous environment, one cool luminous environment and perhaps one more neutral luminous environment for comparison. They did not further explore how warm the luminous environment should be to achieve the most comfort or pleasantness perception for occupants. In our study, three different levels of warm luminous environment were created by the artificial window by attaching different CAR of bronze films, being 100% bronze, 70% bronze and 30% bronze with CCT varying from 2400K to 3900K. Our experiment results are consistent with previous research that participants prefer warm luminous environments over cool luminous environments for comfort and pleasantness. Furthermore, for the warm luminous environment, 30% bronze with CCT 3900K is most satisfying for participants.

The light level, that is, the perception of brightness was also tested in this study. However, no significant difference was found for brightness under the seven luminous environments. The effect of luminous environment with different CCT on brightness has also been investigated by many studies. Most of the studies found that lighting with high CCT resulted in a stronger brightness perception than lower ones [65, 79-81]. However, some studies indicated that warm luminous environment will enhance the perception of brightness [15, 82]. There are also other studies that report differing opinions, Ampenberger et al. [83] indicated that the CCT of a 2700K light source mixing with the CCT of a 5700K light source would achieve the highest perceived brightness ratings when comparing it with solely using a 2700K light source or 5700K light source. In Runqi' s work [55], it was found that a luminous environment with CCT 5000K is perceived brighter than either the warm shift luminous environment (i.e. CCT less than 5000K) or the cool shift luminous environment (i.e. CCT higher than 5000K). The findings of Lee et al. [84] agreed with our results stating that the visual perception of brightness for conducting reading tasks was not significantly affected by colour temperature when the horizontal illuminance was 500 lux. Therefore, it is hard to suggest that a light source with differing CCT will influence the brightness perception in a space [30]. The effect of colour temperature on perceived brightness still nees to be explored further.

In the assessment of alertness, participants perceived the effect of 100% blue, 70% blue, 30% blue, 30% bronze and 100% clear as similar for alertness, with all five luminous environments performing better than 70% bronze and 100% bronze. It is clear that people perceived approximately equivalent alertness under high or medium CCT (i.e. CCT in the range between 9000K and 4000K) luminous environment. But when participants were exposed to a low CCT luminous environment (i.e. CCT lower than 3400K), their alertness was negatively affected. Alertness is significantly related to the non-visual effect of light. When visible light received by eyes and reaches the retina, a series reactions are activated in the photoreceptor cells. At the same time, the stimulus is transformed via the optic nerve to the primary visual cortex and casing vision [85]. In the process, non-visual effect of light was found as the stimulus of light does not only react with photoreceptor cells but also the intrinsically photosensitive retinal ganglion cells (ipRGCs) which would convert the light into the neural signals received by suprachiasmatic nuclei of the brain's hypothalamus region where can regulate circadian rhythms and other biological function of human [9] such as physiology, behavior, mood and alertness. Previous studies [86, 87] indicated that alertness of occupants is not only related to light spectrum and light level but also the timing of light (i.e. morning, afternoon or evening). In the evening or at night, multiple studies have revealed that a high CCT light source may positively affect people's alertness [88-90]. However, for daytime, (i.e. morning and afternoon) findings on such effects are still inconclusive. Rautkya et al. [77] reported that students have higher alertness under a higher CCT light source (i.e. 17000K vs 4000K) in the autumn afternoon, but that alertness was not impacted by colour temperature in the morning. Findings from Iskra-Golec IM et al. s' study [91] showed completely the opposite, they indicated that blue-enriched light (i.e. high CCT light source) had a positive effect on alertness in the morning, but not in the afternoon. Since our experiment was carried in the morning or afternoon, it only can be concluded that in the daytime a low CCT luminous environment (i.e. 70% bronze and 100% bronze) negatively affected participants' alertness.

After finishing the achromatic ring chart test and chromatic ring chart test, task difficultly ratings were also assessed by participants. For achromatic ring chart test, participants perceived no difference in task difficulty across the seven luminous environments. This result corresponds to the findings of our experiment whereby visual accuracy was not influenced by a light source with different CCT. As for the chromatic ring chart test, participants felt they only had difficulty in finishing the task under 100% bronze. Supporting this, participants under 100% bronze did have the worst performance in the chromatic ring chart test. Other luminous environment such as 70% bronze also had a negative effect on the test. This implies that participants' subjective judgement may not be sensitive enough to reflect their objective reaction.

5. Conclusion

In this study, a psychological experiment was carried out in a cubicle illuminated by LED lights transmitted through an artificial window designed to investigate the effect of patterned chromatic glazing on human' perception and performance from four aspects: visual accuracy, colour discrimination, working speed and visual perception. The patterned chromatic glazing was designed and aimed to implement patterns in the chromatic glazing to introduce a two-directional colour distortion altering the colorimetric characteristics of the glazing and also the luminous environment. By applying seven different types of patterned chromatic glazing there were seven luminous environments tested in the cubicle which were 100% clear, 100% blue, 70% blue, 30% blue, 100% bronze, 70% bronze and 30% bronze. A comprehensive measurement was carried out to obtain the colorimetric characteristics of the designed test environment, including the artificial window (light source), surrounding environment (walls) and also the task area. Then the effect of the luminous environment on participants was tested when these participants were completely immersed in the environment.

The findings of the study show that the patterned chromatic glazing conditions created a more desirable luminous indoor environment, as well as a more efficient work environment. Further investigation of the pattern glazing will be investigated to have a full understanding of the patterned glazing on other light condition such as direct light condition. The main results from the analyses can be summarized as follows:

- In terms of visual accuracy and working speed the performance of participants would not be affected by variation of the seven luminous environments. This implies the effect of window glazing with different colour properties was negligible for participants to finish the simple visual accuracy test.
- In terms of colour discrimination, 100% blue resulted in the best performance in the colour discrimination test, while the rest luminous environments were all better than 70% bronze and 100% bronze. It was found participants had a better ability to discriminate colours under high CCT light sources as compared with low CCT light sources.

- In terms of visual perception, participants preferred warm luminous environments over cool luminous environments for comfort and pleasantness. Furthermore, among the warm luminous environment group (i.e. 30% bronze, 70% bronze and 100% bronze), 30% bronze with CCT 3900K would be most satisfying to participants.
- In terms of light level, under different luminous environments with constant illuminance level (i.e. 300 lux) the influence of window glazing with different colour properties is too small for participants to perceive any change of brightness.
- In terms of the two factors, alertness and difficulty rating for chromatic ring chart test, participants prefer the cool luminous environment and gave low ratings to the warm luminous group, aside from for 30% bronze.

It can be concluded that when considering both visual perception and working performance, the patterned chromatic glazing for 30% bronze, 30% blue and 70% blue may be the most appealing choice for occupants. This implies that the design of patterned chromatic glazing which introduces the combination of two chromatic glazings may be a feasible solution to improve the indoor luminous environment. These findings are potentially valuable to supply to architects or builders to aid in finding an appropriate way to design building fenestration.

This research used a mock up office comprehensively test the effect of luminous environment on participants' performance, where seven patterned windows were introduced. However, this experiment was conducted based on 27 participants aged between 17 -30. Considering the influence of age on visual perception including visual accuracy [92, 93], the experimental results only validated for young adults (i.e. 17-30). LED light sources was used in this research to simulate the daylight for the experiments and maintain a controlled luminous environment. However, differing from the daylight with continue light spectrum, the LED light has a discontinue light spectrum with a peak spectrum appearing between 450 and 470 nm which has effect on human's non-image effect such as alertness, mood, circadian rhythms, and well-being [94]. Therefore, the using of LED lights cannot create an identical luminous environment as that of daylight. However, the using of LED light source can offer the test room with constant condition while can be adjusted according to needs. In addition, there is a lack of consideration of controlling timing of light (i.e. morning, afternoon or evening) which may affect the result of non-visual effect (i.e. alertness and sleepiness). The further work will cover the limitation of current work. It was suggested to invite more participants that including young adults, middle-aged adults and old adults to take the experiment. And the effect of age, gender and ethnic background of these participants can be analysed. In addition, the experiment for assessing the non-visual effect of light on participants can be improved by referring the guide [95] to report light exposure in biological function of human. When considering the evaluation of visual perception colour perception of occupants is also an important factor as it can be significantly affected by the spectral properties of window glazing. In future work, the assessment of colour perception under different pattered chromatic glazing will also be carried out to better understand the effect of different types of glazing on human visual perception.

Appendix A:

For each luminous environment, illuminance is maintained at approximately 300 lux. A Konica Minolta CL-200A chroma-meter (accuracy ± 0.02 %) was used to inspect illuminance on the vertical surface (i.e. the central of the desk) and horizontal surface (i.e. the central of the front door for visual task). Although illuminance is maintained for each scenario, the spectral properties of the transmitted light may be significantly changed with the applying of different patterned chromatic films. Therefore, a calibrated Ocean Optics Spectrometer USB2000+UV-VIS was used to measure the spectrum of the transmitted light. The setting for the measurement is shown in Fig. A.1. Considering light transmitted through the glazing attached with patterned chromatic films may result non-uniformed distribution of light. Nine points on opposite surface that directly across from the artificial window were determined as the measured points. The measuring surface is 0.2 m away from the artificial window position which is in the middle position between the position of participants and artificial window. The nine measured points that indicated by number 1,2,3…and 9 are distributed uniformity on the measuring surface. The cosine corrector probe is fixed by an adjustable bracket on each point to collect the light transmitted through the glazing of artificial window from a 180° angle, it has been connected with optical fiber to the Ocean Optics Spectrometer USB2000+UV-VIS.

The measured the spectrum of light transmitted though the glazing with the seven different patterned chromatic films are given in Fig. A.2. It can be seen that for each scenario, there is no significant differences for the light spectrum among the nine points. This indicate that in this designed condition the using of patterned chromatic glazing would not result non-uniformity distribution of transmitted light. It may be because a diffused light source was selected whilst the interior surfaces were painted matte-white which can evenly diffuse the incident light, therefore, the transmitted light has been mixed uniformly in the test room before received by the cosine corrector probe and the spectrometer. In addition, it can be seen that 100% blue glazing has a strong peak in the 450 nm (blue) region while the 100% bronze glazing has a peak response in the region between 600 and 630 nm. They both significantly differ from that of 100% clear glazing. Furthermore, when introducing clear film into 100%blue and 100%bronze glazing, the spectrum of transmitted light has been changed as shown in Fig. A.2 (a), (b), (d) and (e). It can be seen that the patterned chromatic glazing combined the spectral properties of the light for both clear and chromic glazing where it show the characteristics for both clear and bronze.

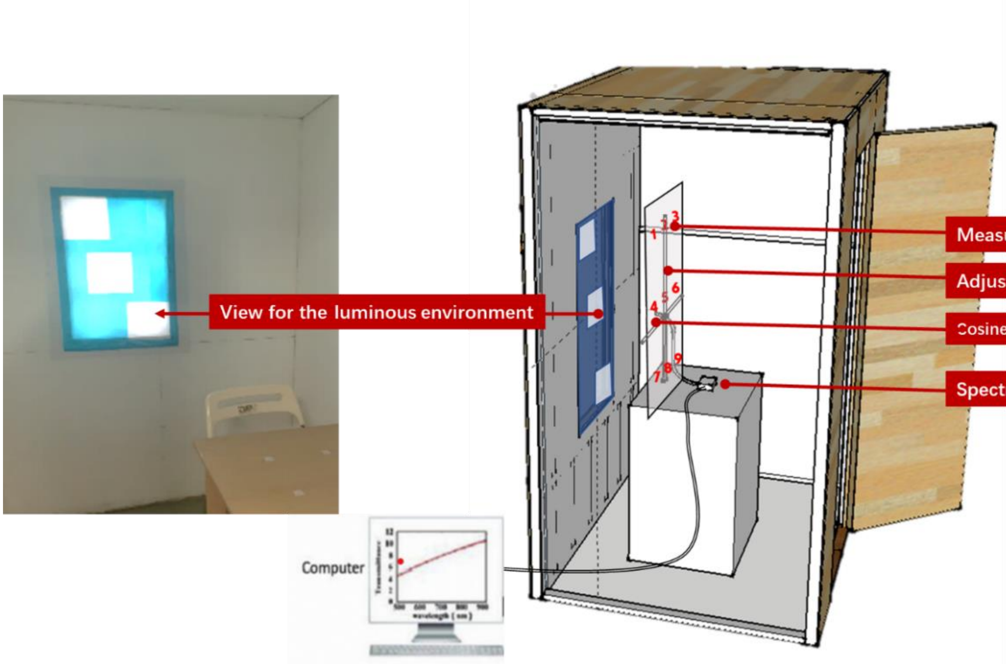
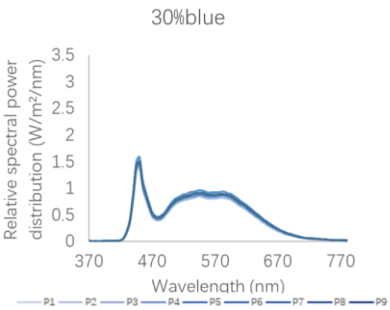
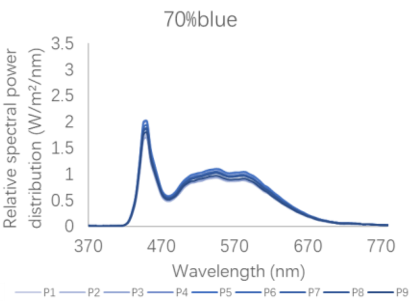
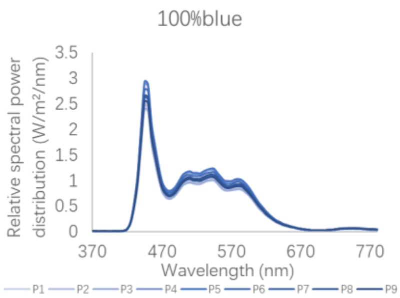


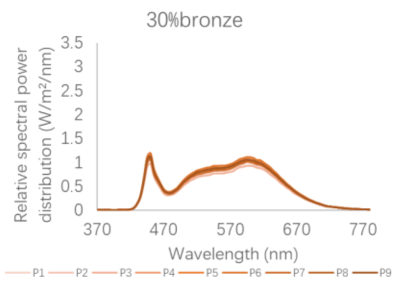
Fig. A.1 Schematic of the spectrum measurement.

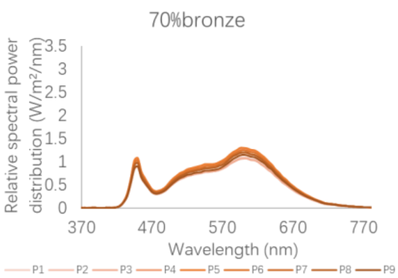


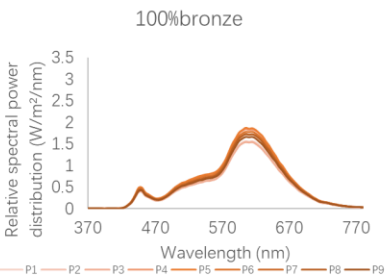




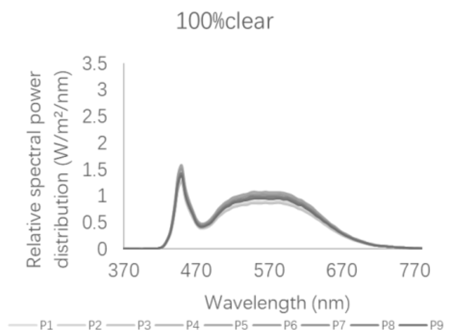
(a) 30%blue (b) 70%blue (c) 100%blue







(d) 30%bronze (e) 70%bronze (f) 100%bronze



(g) 100%clear

Fig. A.2 Spectrum of light transmitted though the artificial window.

Based on the measured light spectrum, the colorimetric characteristics of the transmitted light for the seven luminous environments can be determined. The chromaticity coordinates of the light spectrum have been illustrated on the CIE 1931 chromaticity diagram as shown in Fig. A.3. The colour appearance of transmitted light can be observed from background colour of the diagram. 100% blue, 100% bronze and 100% clear glazing appear blueish colour, brownish and neutral colour, respectively. As for the patterned chromatic glazing, it was found that with increasing of the covering area ratio of clearing glazing (i.e. from 30% to 70%), the colour appearance of the patterned glazing gradually becomes from the bluish or brownish colour to be close to neutral colour.

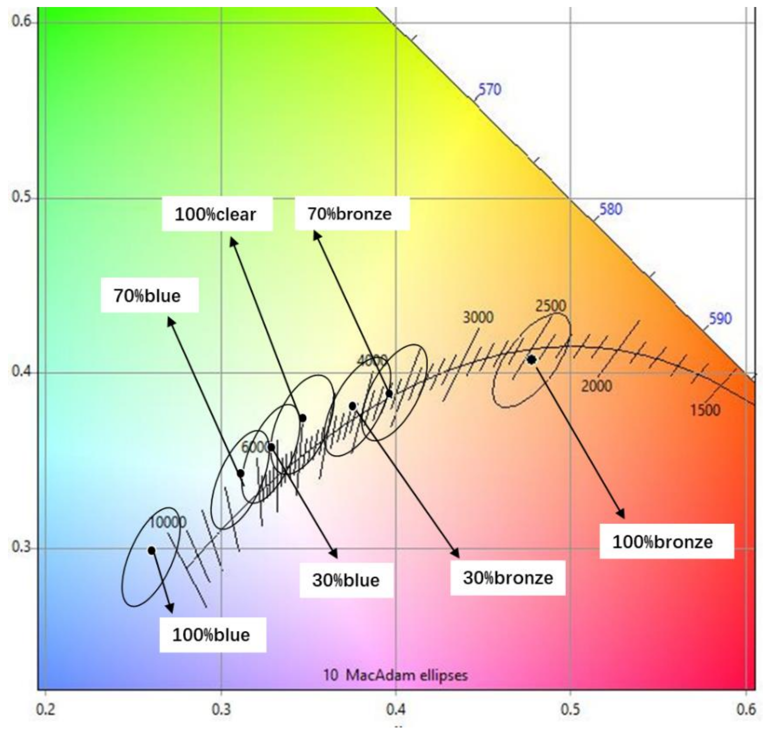


Fig. A.3 Chromaticity coordinates for the light of the seven luminous environments on CIE 1931 chromaticity diagram.

Appendix B:

Table B.1 Summary of statistical analysis for the experimental data.

Data	Either assumption of normality or homogeneity was violated	Statistical test: assessing significant difference for the seven luminous environments	Post Hoc test: assessing significant difference for paired comparison
Objective test: error_c, time_c, error_a, time_a	No	Non-parametric Friedman's ANOVA test	Wilcoxon Signed-Rank test
Subjective test: overall comfort, light level, pleasantness, alertness, difficulty of achromatic ring chart test, difficulty of chromatic ring chart test	Yes	Repeated-measures ANOVA test	Paired sample t-test

CRediT authorship contribution statement

Dingming Liu: Methodology, Investigation, Data curation, Writing - original draft, review & editing. **Janos Kovacs-Biro**: Methodology, Investigation, Writing - original draft. **Karen Connelly**: Methodology, Writing - review & editing. **Fedaa Abd-AlHamid**: Methodology, Writing - review & editing. **Yupeng Wu**: Resources, Funding acquisition, Supervision, Methodology, Writing - review & editing.

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