Development of experimental methods for quantifying the human response to chromatic glazing

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Abstract

Thermochromic (TC) windows have the ability to regulate daylight and control the solar heat gains that shape a building's internal environment. They therfore offer the potential to improve indoor comfort and reduce building energy demand when used in place of traditional clear glazing systems. However, the quality of the luminous environment is affected due to their chromatic appearance (e.g. common TC coatings impart a bronze or blue hue), resulting in changes to correlated colour temperatures (CCT). Previous studies show that experiments performed under daylight conditions are difficult to be control, while those conducted under artificial lighting conditions cannot faithfully reproduce window properties. In order to investigate the influence of TC windows on visual performance and comfort of subjects in an efficient and economical way, an innovative test room cubicle was designed. It is a mock-up office lit by an artificial window, simulating luminous conditions filtered through two types of TC window (one blue tinted and one bronze tinted). Clear glazing was used as a reference. Objective visual tasks involving Landolt charts and subjective assessments made using questionnaires were used to determine subjects' response to the three different luminous conditions. Results show that the experimental method is effective at determining human response to chromatic glazing. Additionally, the method is flexible due to its small scale and its ability to artificially represent different window types.

Keywords: Chromatic glazing; Mock-up office; Visual performance; Subjective assessment; Artificial window.

1. Introduction

Humans spend most of their time inside buildings, for example, it is estimated that many office workers spend up to 90% of daylight hours at their place of work [1, 2]. Building standards encourage designers to deliver task lighting to cater for the visual needs of occupants [3]. This is instrumental in providing clarity of the tasks occupants are commonly engaged in and to reduce visual stress, eye fatigue and headaches [3-6]. Effective illumination of the indoor environment has therefore become an important attribute in the workplace, one that plays a significant role in determining occupant performance [1].

Thermochromic (TC) windows are considered as promising building components, capable of regulating – dynamically and automatically – the indoor thermal and luminous conditions and achieving potential energy savings [7-9]. Previous studies of TC technology in building applications mainly focused on development of the TC material and on its influence on building energy performance [10-12]. Additionally, a limited number of studies have explored the effect of TC windows on daylighting distribution and uniformity [9, 10].

In studies focusing on TC window development, the influence of the window colour (i.e., brown, blue, etc.) on occupant response to the luminous environment created within internal spaces is rarely considered. In rooms served by TC windows, daylight transmitted into space after having undergone spectral transformation determined by the glazing's optical properties would be one of the main sources of illumination. Therefore, the colours used in the TC windows will also modify the colour rendering of objects and surfaces that make up the indoor visual scene.

To investigate the effects of chromatic and TC glazing, the visual response has commonly been evaluated under two types of luminous environment: daylit and artificially lit.

1) Experiments under daylit conditions

Daylight emitted from the sun as electromagnetic radiation has a continuous spectrum power distribution spans all parts of the visible wavelength range. However, depending on meteorological conditions (i.e., time of the day, latitude, weather, etc.) daylight transmitted into a building changes over the time, sometimes gradually and sometimes suddenly. This presents challengfes in relation to ensuring a consistent and reliable light source and is one of the limitations of conducting experiemnts using daylight as the source of illumination.

Most of the studies conducted under daylit conditions [1, 13-15] have used small-scale models to simulate the visual scene and investigate the visual perception of different glazing types. This is in part due to cost and in part because it is easier and quicker to change the window types during the experiemnt when working at scale, This approach means that instead of performing experimental tasks in full-scale test rooms, these studies [1, 14-23] required observers to look into the scale model; and make subjective assessments of quantities and qualities such as brightness, naturality, shadows, beauty, and pleasantness

Typically, small-scale models have been used to assist in the design of the fenestration in order to investigate daylight distribution patterns. Bodart [24] states that scale choice should be depended upon different design considerations, in particular when studying the accuracy of diffuse and direct daylight conditions. When considering experiments using measurement devices or involving user assessment, the most suitable scales recommended lie in the range between 1/10 and 1/1 [24]. Additionally, the distribution of light within small-scale models was found to be more similar to the full-scale model in cloudy (diffused) sky conditions [25, 26].

Dubois and Cantin [15] used a 1:7.5 scale model to investigate the visual responses of subjects under the effect of six coated glazing materials. In particular, they were interested the relationship between the interior conditions in the model and the view to the outdoor environment using subjective assessments about naturalness, colour temperature, pleasantness, visual comfort, and shadow. Additional studies by the same authors were used in two tests using 1:6 scale models where they implemented the same methods. They obtained the same results in both studies, i.e., higher transmittance glazing led to more positive ratings for naturalness, pleasantness, and sharpness [14]. Arsenault *et al.* [1] and Vossen *et al.* [27] also conducted experiments into the visual responses of subjects to chromatic windows using 1:4 and 1:6 scale models respectively.

2) Experiments under artificially lit conditions

Several test procedures have been developed and are commonly used to examine the effect of lamp spectrum on apparent brightness in controlled, artificially lit, test room conditions [28, 29]. The side-by-side brightness matching procedure uses two adjacent identical interior visual scenes where the observer is required to adjust the luminance of one scene until the two interiors (as near as possible) meet prescribed visual criteria [30-33]. In the brightness ranking procedure subjects are sequentially presented with two sources of fixed illuminance and instructed to identify which of the conditions appears brighter [33, 34]. The category rating procedure, typically, uses semantic differential rating scales, whereby the observer is required to rate the brightness of an interior on a seven-point scale from dim to bright [35].

Studies by Creveld, Manave, and Wei *et al*. [16, 18, 36] examined subject visual responses to changes in illuminance, CCT, and explored the relationship between the two.

3) Methods to assess human response to different luminous environments

Common approaches that may be used to determine a subject's response to the visual scene fall into two broad categories: objective tasks and subjective assessment.

Table 1 presents the main approaches that have been adopted in previous studies. To evaluate visual performance, objective tasks that measure accuracy (freedom from errors), rate of performance (speed), and reaction time have been used to gather data from subjects subject to different lighting conditions.

For example, in a study by Fotios [37], 30 subjects were instructed to perform tasks lit by different types of commonly used street lamps with different spectral power distribution. A series of tasks were carried out under each lamp type, including reading the gap directions of Landolt rings, and naming the colours in Gretag Macbeth colour checker chart. The influence of the light source was determined by a calculation of error rate under the different test conditions.

Table 1: Commonly used factors affected by different lighting environments and methods to test the human performance objectively and subjectively

Main Factors	Method	Aims	Reference
Objective assessments			
Visual acuity	Landolt rings Snellen charts	Investigate the influence of treatment conditions on the clarity of vision	[16, 17, 37, 38]
Contrast	Pelli-Robson Contrast Sensitivity chart	Test the contrast of a target surface relative to the luminance of its background	[39, 40]
Colour naming	Gretag Macbeth colour checker chart; 24 colour samples: semantic rating	Explore the influence of lighting conditions on colour discrimination	[41, 42]
Test reading, writing/ typing	Letter searching Typing/writing	Test if the different lighting conditions influence concentration	[17, 40]
Subjective assessments			
Arousal	Subjective scales: Likert scale Bipolar scale Visual analogue scales (VAS)	Test the degree of alertness caused by different lighting conditions	[1, 14-23]
Light level		Test the perception of brightness	
Colour temperature		Test the perception of cool or warm light	
Naturalness		Test whether visual conditions create a luminous environment that appears artificial	
Pleasantness		Test whether lighting conditions change the mood of an observer	
Comfort		Test whether the visual conditions produce feelings of discomfort (i.e., glare)	

Sharpness		Test whether lighting conditions create visual targets that are blurred	
Shadows		Describe characteristics of shadows (i.e., blurred or sharp, soft or hard)	
Spaciousness		Describe whether the visual conditions make the room feel spacious or narrow	

In addition, subjective measurements using questionnaire surveys have also been used. For instance, Borisuit *et al.* [23] collected information on, respectively, visual comfort, alertness, and mood, under different daylit and artificially lit conditions. While in a test room, the subjects were required to evaluate various conditions using visual analogue scales.

The review of experimental methods presented in sections 1 and 2 shows a number of advantages and disadvantages. Experiments performed under daylit conditions have the advantage of emulating the daylight distribution that would prevail inside a full-scale building. However, the natural variations in daylight level and quality represent an uncontrolled variable in experiments and have to be countered by taking a large number of samples is required and data analysis is more complicated. Additionally, subjective assessments made by looking into a scaled model instead of being present in a full scale room might restrict the perception of subjects, e.g. the observation position is likely to be quite different from that in practise. Unlike daylit conditions, artificial lighting conditions offer a larger degree of control over the luminous environment (i.e., illuminance and CCT). This allows the researcher to easily vary the visual conditions and also test a wide range of experimental variables.

Taking all of this on board, a novel and economic experimental method is presented in this paper that is designed to evaluate how human visual performance is affected by chromatic glazing. The experimental apparatus and associated methods for determining human response improved the efficiency with which experimental conditions could be changed when doing multi-levels repeated measures. By using controllable artificial windows to simulate the daylit conditions, the method is flexible enough to adjust and monitor the luminous conditions, including correlated colour temperatures and illuminance levels within the test environment. This is occupied by the test subjects who are able to complete tasks and from whom the collection of objective and subjective responses is straightforward.

2. Experimental method

The experimental method described in this section is designed to provide controlled laboratory conditions within which to test the visual responses of subjects working in an environment lit by simulated glazing with different thermochromic films.

Based on the design of an artificial window proposed by Mangkuto *et al.* [43], an array of lighting emitting diodes (LEDs) was used to simulate the daylight entering a small test room through a window. Different chromatic films could then be applied to the artificial window, to quickly modify the luminous environment within the test room which was occupied by a human subject. For the experiment described here, 31 subjects were recruited to perform a series of visual tasks, and questionnaires surveys were used to assess the luminous conditions during each of the test sessions.

3.1. Experimental setup

3.1.1. Test room and artificial window

For the study described here, a controlled setting allowed the use of different coloured films exhibiting similar photometric properties to TC glazing to be used to study subject response to the simulated luminous environment.

Figure 1 shows the test room which was built inside a laboratory space within the Energy Technologies Building (ETB) located at the University of Nottingham. This test room was made from wooden partitions and provided a space with dimensions of 1.5 m (length) ×1.2 m (width) × 2.1 m (height). The size of the test room is based on the recommendations for workspaces contained in UK health and safety standards (i.e., the minimum space for per person should be not less than 11 cubic meters (11 m^3) with a ceiling height of no more than 3 m) [44]. Previous studies indicated that if tests are conducted using scale models these should be in the range 1:1 - 1:10 if they are to be used to perform subjective assessments [24]. The size of this test room was selected such that it provides an experimental space size is easily accessible for test subjects and it lies within the recommendad range of scales for a scale model study (i.e., with a volume of 3.78 m^3, it is built to a scale of approximately 1:3 when compared with the recommended minimum volume of 11m^3). To evenly diffuse the lighting inside the test room, the interior surfaces were painted matte-white.

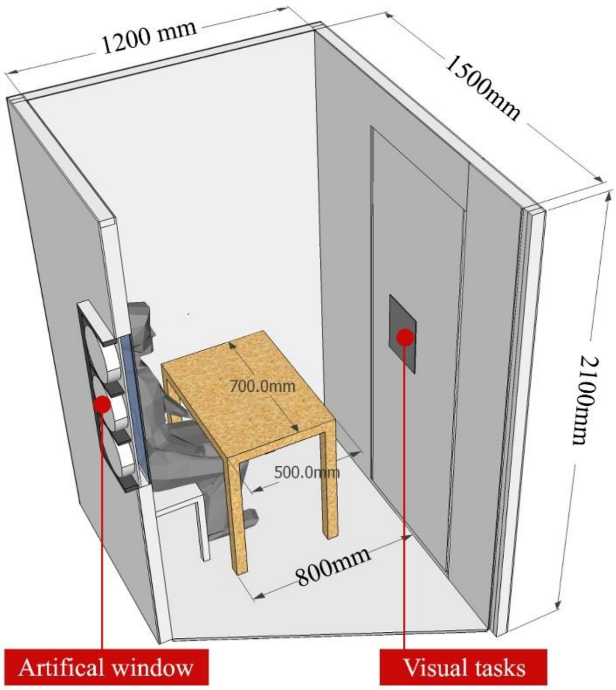
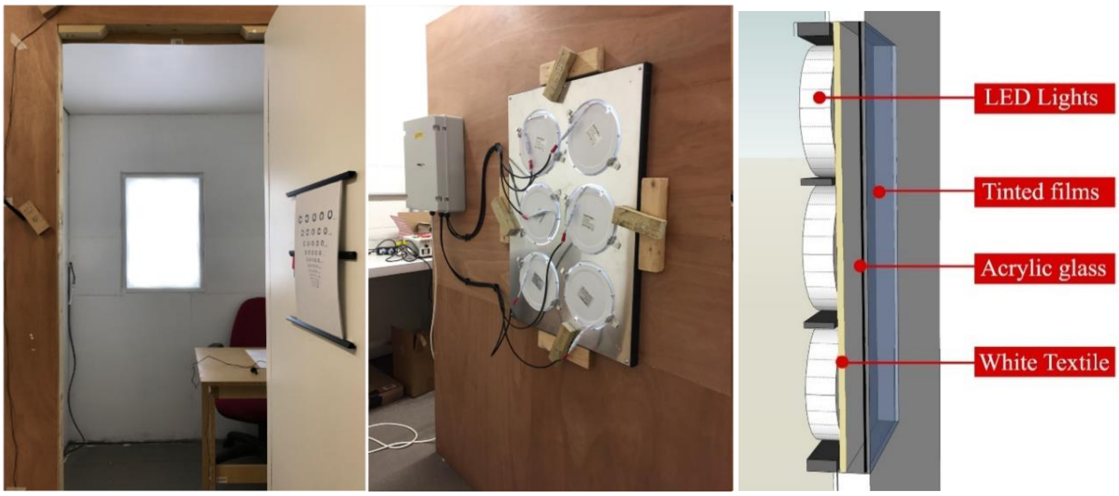


Figure 1: Schematic of the test room with test subject positioned inside

An opening of dimensions 0.54 m × 0.72 m was placed in one of the walls to accommodate the artificial window, which was set with a cill height of 0.9m above floor level. Figure 2 shows photographic images of the integrated artificial window components seen from outside of the test room and a section illustration of the various layers used to provide a uniform, diffuse light source. The artificial window which was located in the opening comprised 6 LEDs positioned behind a white fabric diffusing layer and a sheet of perspex. On the wall opposite the artificial window, an area was created where visual tasks could be mounted. The distance between the artificial window and the visual tasks was 1.2 m. Based on the design considerations of Mangkuto *et al.* [43], the artificial window consisted of a light source, light filter and front cover glazing.



(a) Interior view of test room (b) exterior view of test room and artificial window (c) Section through artificial window

Figure 2: The configuration of the designed artificial window

A total of 6 Lightwell 18 W LED Frosted Ceiling lights were mounted to form a compact array. As is shown in Figure 3, the spectral irradiance of the LEDs , measured using an Ocean Optics Spectrometer USB2000+UV-VIS was approximate to natural daylight, althouth LEDs have a narrower spectrum range than daylight (380-780nm), the sensitive range of human eyes (under photopic conditions, 400-700nm) falls into the measured range of LEDs [45]. Therefore, it mades them ideal luminaires to be integrated into the artificial window.

Each LED light has a lumen output of 1390 lm with a beam angle of 120^{o} and a CCT equal to 6500 K (cool white). The LED array could be controlled by a dimmer switch to vary the luminous environment inside the cubicle. To avoid producing any direct light, white textile fabric with diffusive properties was used to filter light and create diffused conditions inside the test room. The fabric was then covered by 3mm clear acrylic containing a visible transmittance ($\tau \approx 90\%$) and the spectral transmittance almost constant across the wavelength of visible light (380-780 nm).

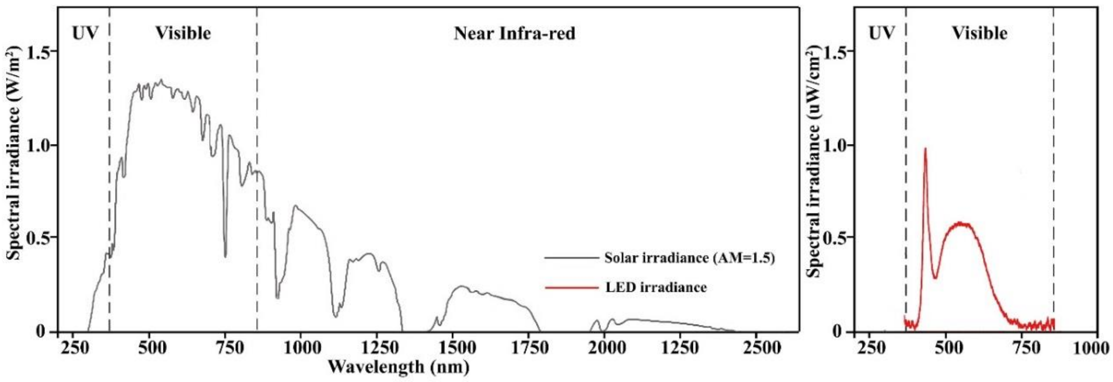


Figure 3: Solar spectral irradiance (left) and lighting spectrum through clear acrylic glazing (right)

3.1.2. Thermochromic window films

According to the literature, there are two types of thermochromic materials. Type 1 materials comprise vanadium oxide (VO_2) - based thermochromic films, which imposes slight changes in the visible spectrum (e.g., 380-780 nm) and larger changes in the near infrared spectrum (e.g., >780 nm) [11, 46]. Within this class of films, VO_2 nanoparticle (i.e., VO_2_Nano) films in particular are capable of changing the transmittance of incident radiation in response to changing temperature – when this rises above approximately 60°C the film tints, giving it a bronze visual appearance [34]. Type 2 materials include a series of composite films of ionic-liquid-nickel-complex-polymer. These films also change the visible transmittance in response to changes in temperature. Film containing $[bmim]_2$ $NiCl_4$ (i.e., TC_IL-Ni^{II}) has a visible transmittance that reduces when temperature increasing from 25 to 75°C. At 25°C, the films has a clear appearance and it tints to a blue visual appearance at 75°C [12, 47].

As the thermocromic materials explored in this study are not commercially available, plastic films with similar photometric properties to tinted Type 1 and Type 2 films were used to investigate visual responses within the test room cubicle. This provided additional benefits as it prevented localised changes to the transmittance that would have occurred in response to heat from the artificial light source if TC materials had been used. In a natural setting, it should be expected that, when the state of the TC glazing changes colour, other extraneous environmental conditions may also vary (i.e., the temperature). These changes can be avoided when using sample films.

Figures 4 (a) and (b), provide the visible spectral transmittance of the two thermochromic substitute materials measured using a calibrated Ocean Optics Spectrometer USB2000+UV-VIS. The blue lines represent the visible spectral transmittance performance of the actual TC materials in their tinted state, while the red lines represent the spectral transmittance of the tinted films used in the test room. It can be seen that the photometric properties closely match the actual VO_2_Nano and TC_IL-Ni^{II} products in their tinted state.

Figure 4 (c) shows a comparison between the light spectrum transmitted through bronze (used to represent VO_2_Nano), blue (used to represent TC_IL-Ni^{II}), and clear glazing films using the LED luminaires at the light source. It can be seen that outside of the region around 440nm blue film has a strong peak in the 440nm (blue) region and gentler peak in the 500 - 550nm region. The bronze film has lower response in the 440nm region and a peak in the region between 570-650nm (yellow/red).

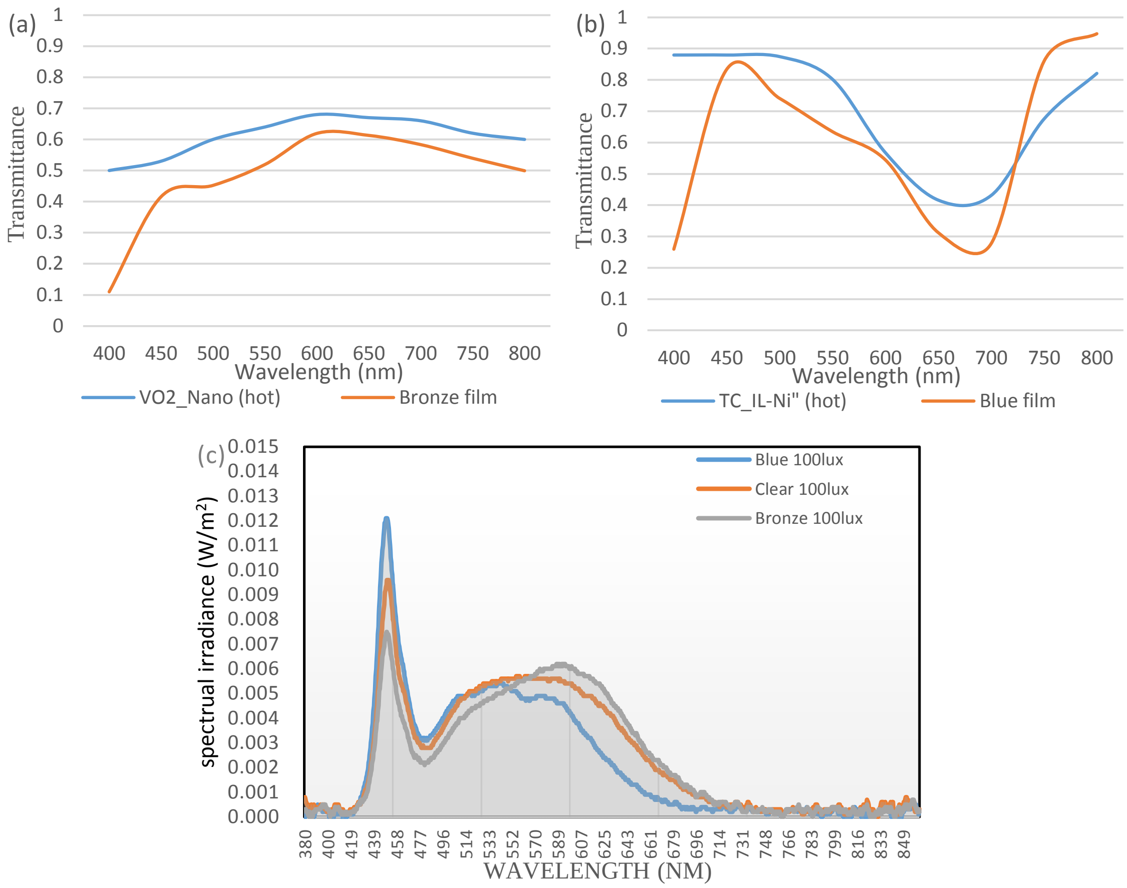


Figure 4: Spectral properties of the TC windows at the tinted state and the selected colour films [12, 47]

Figure 5 shows photographic images of the view inside the test room cubicle lit by the artificial window through the films simulating the visual properties of the VO_2_Nano (a), TC_IL-Ni^{II} (b) thermochromic glazing, and the clear glazing without attached coloured film (c), respectively.

(a) Window with bronze film **(b) Window with blue film** **(c) Clear glazing window**

Figure 5: Photos of lighting environment for the experimental chamber with three different films

3.1.3. Photometric lighting conditions

Inside the test room, the parameters known and alleged to influence visual perception, such as illuminance levels, temperature, and relative humidity were held constant or monitored closely. Temperature and humidity were constantly measured using a small probe. On average, the temperature inside the chamber was maintained at approximately 25^{o}C, and humidity in a range between 45%-55%. According to CIBSE Guide A, this equates to an environment with moderate thermal comfort [48].

By adjusting the luminance output of the dimmable artificial window, the illuminance on the vertical surface on the visual targets was maintained at a value of approximately 100 lux under each of the conditions (Table 2).

One aim of this study was to determine whether different TC films influence human visual response. To assist with this aim, the use of low levels of illumination are recommended (i.e., human visual responses under threshold conditions) [45] to prevent perfect visual acuity scores across all test conditions (i.e., test trials without any errors), and therefore the effect of the TC film would have been negligible. However, under low levels of task illuminance, more errors are likely to be recorded when test subjects perform the Landolt chart test under each of the chromatic films. This would have increased our chances of finding the effect of experimental interest in this investigation. In this study, the threshold method was applied to choose the illuminance level of 100lux, which is considered to be the lowest limit of illuminance level that people could accept in the working environment [49]. While under this threshold luminance condition, the suprathreshold of visual task performance was measured, i.e., the largest magnitude of accuracy.

Table 2. Illuminance level in lux and correlated colour temperature in K under different treatment conditions for vertical and horizontal surfaces

	Vertical surface		**Horizontal surface**	
	Illuminance (lux)	CCT(K)	Illuminance (lux)	CCT (K)
1.Bronze window	103	4056	88	3992
2. Clear window	102	4911	89	4848
3. Blue window	101	7054	85	6932

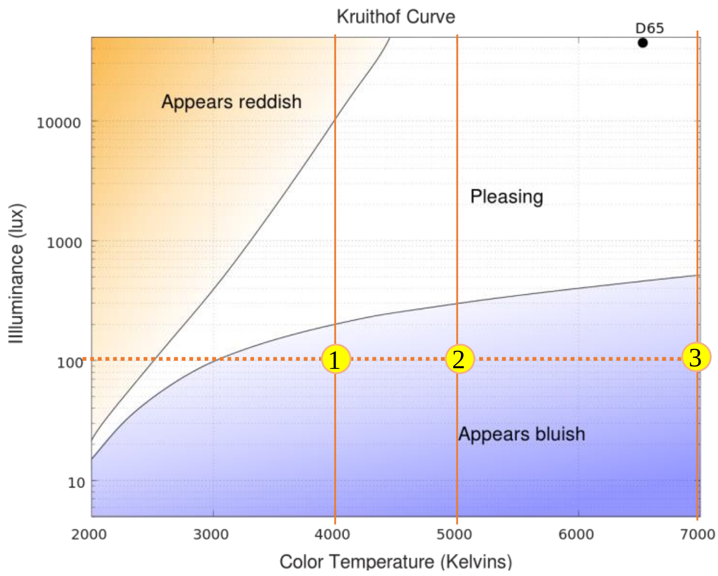


Figure 6: Kruithof curve with measured CCT: Point 1 = Bronze; Point 2 = Clear, and Point 3 = blue window condition.

The illuminance and CCT values on the vertical wall surface (i.e., task position) and horizontal (desk) surface were measured using a calibrated Konica Minolta CL-200A chroma-meter. By changing the films attached to the artificial window, the visual conditions inside the test room cubicle could be easily and quickly changed. The main difference across the three conditions can be seen in the measured values of CCT, as is shown in Table 2. The values of CCT obtained on the vertical and horizontal surfaces are similar: approximately 4000 K for the condition with simulated VO_2_Nano window, 5000 K for the clear window, and 7000 K for that with the simulated TC_IL-Ni^{II} window.

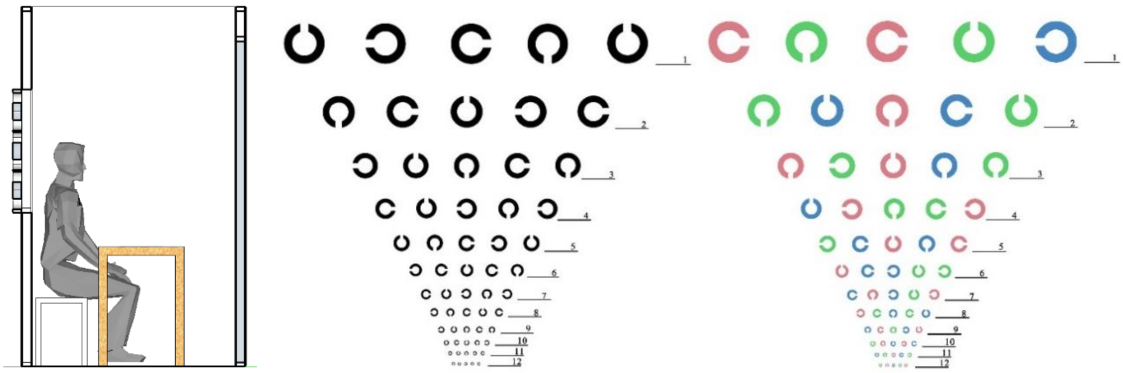
The Kruithof chart was also used to demonstrate the expected visual appearance of the combined illuminance and CCT values as shown in Figure 6. It is noted that, under a fixed illuminance of 100 lux, Kruithof curve reports that observers may feel the working environment is bluish under all three conditions with CCT ranging from 4000 K to 7000 K [50]. However, under this low level of illumination (i.e., < 300 lux), the effect of the different tinted films on subject visual responses is not yet known.

3.2. Visual tasks

The Landolt ring chart was used to measure visual acuity and colour discrimination of test subjects. It has been shown that visual tests performed using Landolt rings are repeatable and relatively accurate [37].

The two charts used in this study are shown in Figure 7. The charts were mounted on the test room wall, directly opposite to the artificial window at a distance of 1.2 m. In each test session, only one chart was presented to the test subject.

Both achromatic and chromatic acuity were measured using black (Figure 7(b)) and coloured (Figure 7(c)) ring charts, respectively. In a repeated task, the colour naming test was also carried out the Landolt ring chart in Figure 7(c). To ensure a constant background luminance, the charts were printed on matte white paper with similar optical properties found on the interior surface of the test room. This prevents unwanted contrast effects between the task and its immediate surroindings when mounted on the test room wall.

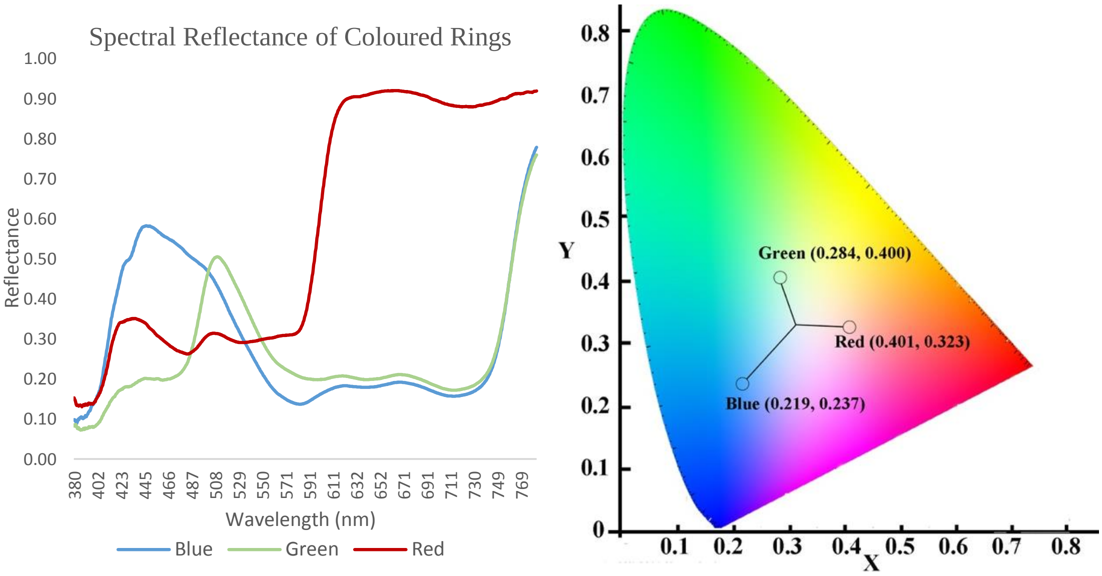


(a) viewing position of the subject (b) achromatic Landolt rings (c) chromatic Landolt rings

Figure 7: Section view of the subject viewing position inside the test room. Achromatic and chromatic Landolt rings used in objective tasks (not to scale)

There are 12 rows in total with five Landolt rings on each row. From top to bottom, the size of each row decreases by 0.1 log unit compared with the row above. Based on the viewing position used in this study, the size of the Landolt rings was adjusted meeting the standard of visual acuity test at a 1-meter distance [51, 52]. The largest ring is equivalent to the size of 8.0 M letter (where M-units specify the height of typeset materials ie 1M= 1.5 mm), and the smallest one to 0.63 M letter. The the gap size ranged from 10.8 min of arc to 0.6 min of arc at the viewing position.

For the chromatic Landolt ring chart, three colours of rings were used based on the literature [37]: red, blue and green, representing the three main components of the RGB colour model. The total number of rings were identical tin the achromatic and chromatic tasks, but the directions of the gaps in the rings were randomly changed to avoid unwanted learning effects. The three colours were measured by following the NIST spectral calibration standard using an Ocean Optics spectrometer USB2000+VIS-NIR-ES and Halogen Lightsource HL-2000 (Table 4). WS-1 Reflectance Standards (Table 4) were used to measure the spectral reflectance of each printed colour ring. Figure 8 illustrates the measured spectral reflectance of each colour and also the position of each in the Chromaticity diagram: red (x=0.401, y=0.323), green (x=0.284, y=0.400), blue (x=0.219, y=0.231).



(a) Spectral reflectance of printed coloured rings (b) the position of three colours on the chromaticity chart

Figure 8: Spectral reflectance and Chromaticity under a standard D65 light source

Under the three different window conditions (clear, bronze and blue), the luminance contrasts of the achromatic and chromatic chart were measured (Table 3) using a Minolta LS-100 luminance meter (Table 4). According to Weber's formula, contrast (C) is calculated using the background luminance (L_b) and target luminance (L_t) of each chromatic ring according the Equation [1]:

$$C=\frac{L_t-L_b}{L_b} \qquad \text{Equation [1]}$$

Here, the background luminance is the immediate surroundings of the Landolt rings papery that of the paper on which they were printed, and the target luminance is the luminance measured on the rings themselves.

Table 3: Background and target (black, green, red and blue ring) luminance, and corresponding contrast.

		Clear		Blue		Bronzr	
		Luminance (cd/m^2)	Contrast	Luminance (cd/m^2)	Contrast	Luminance (cd/m^2)	Contrast
L_t	Black	2.45	-0.92	2.24	-0.92	2.14	-0.93
	Green	12.02	-0.60	11.7	-0.58	11.11	-0.62
	Red	13.35	-0.56	11.74	-0.58	13.29	-0.54
	Blue	8.32	-0.72	8.19	-0.71	7.50	-0.74
L_b	Background	30.01		27.91		28.92	

Table 4: Specification of apparatus.

Brand	Model	Accuracy	Measurement	Reference
Ocean Optics	Spectrometer USB2000+UV-VIS	Signal-to-noise ratio: 250:1 (at full signal) Resolution: 0.1-10nm varies by configuration	reflectance, transmittance, irradiance	[53]
Ocean Optics	Halogen Light source HL-2000	0.25% Stability of optical output	Provide lighting	[54]
Ocean Optics	Reflectance Standards WS-1	Reflectivity >98% for 200-1500nm	Standard reflectance	[55]
Campbell Scientific	Temperature and relative humidity probe CS215	Accuracy ± 0.4 °C for temperature and ± 2% for humidity	Temperature; humidity	[56]
Konica Minolta	Chroma-meter CL-200A	±2% Accuracy ±0.2% Repeatability	Correlated colour temperature(K); illuminance (lux)	[57]
Konica Minolta	Luminance meter LS-150	±2% Accuracy ±0.2% Repeatability	Luminance (cd/m^2)	[58]

3.3. Questionnaires

At the beginning of the study, general demographic information from the subjects (i.e., age, gender, visual acuity (i.e., whether they wear glasses or contact lenses), and ethnic background) were collected.

During the experiment, self-assessments of several temporal variables, including caffeine intake, hunger levels, fatigue levels and sleepiness levels were recorded.

Fatigue levels were evaluated using the Sam-Perelli scale (SPS). This utilises a 7-point scale, whereby 1 represents a condition of fully alert and 7 represents a state describing a condition of being completely exhausted. Sleepiness levels were evaluated by the Karolinska Sleepiness Scale (KSS). This records evaluations on a 9-point scale, whereby 1 represents a condition of fully alert and 9 correspond to a condition of being fully sleepy. Since the descriptors on the SPS and KSS are relatively similar to each other, the SPS was used as the primary measure of fatigue levels in this study [59].

In addition, five-point Likert scales using semantic bipolar words were used to obtain subjective assessments of the luminous environment using the 16 questions shown in Table 5. These are designed to elicit subjective assessments of light level, distribution, naturalness, and pleasantness as well as colour appearance, and overall visual comfort. Based on the literature, most of these factors play a significant role in determining how the quality of the indoor luminous environment can be described.

Table 5: Questions and the bipolar descriptions of the answers in the questionnaire

	Questions	**Bipolar descriptions**
Q1	I perceive the room as a whole to be	Dark---Bright
Q2	Would you like to have had extra lighting during the test?	Always---Never
Q3	How would you describe the lighting in the room?	Tinted---Clear
Q4	How would you describe the feel of lighting in the room?	Cool --- Warm
Q5	How would you describe the colours in the picture on the wall in front of you?	Artificial---Natural
Q6	How easy was it for you to identify the colours of the rings in the test?	Difficult --- Easy
Q7	My skin or clothes have an unnatural look in this room	Strongly disagree---Strongly agree
Q8	It was difficult to identify the gap orientation of the rings in the test?	Strongly disagree---Strongly agree
Q9	On a work day, I could work under these lighting conditions for	<1h; 1-3h; 4-5h; 6-7h; >7h
Q10	How would you describe the light distribution in this room?	Uneven---Uniform
Q11	The lighting in the room is	Unpleasant---Pleasant
Q12	The lighting in the room makes me feel?	Sleepy---Alert
Q13	The lighting conditions in this room make me feel calm	Strongly disagree---Strongly agree
Q14	How does the lighting condition in this room compare with the lighting of the space where you currently work?	Worse---Better
Q15	Overall, the lighting condition in this room is	Uncomfortable---Comfortable
Q16	Do you think this lighting environment is appropriate for office work?	Unacceptable---Acceptable

3.4. Experimental procedure

During an initial test using 6 subjects, the experimental procedure was piloted to verify its feasibility. The main experiment was then conducted during June 2017, and lasted 15 working days. The experimental procedure and questionnaires applied to the study were all assessed and approved by the University ethics committee.

The main experiment involved a total of 31 volunteers recruited from the Energy Technologies Building from the University of Nottingham using online advertisements. Subjects were all postgraduate students, between the ages of 20 and 45 years, 24 male and 7 female. None of the subjects reported any visual problems (i.e., colour perception) and 16 subjects wore corrective lenses during the experiment.

The initial part of the experiment involved the subjects reporting to a rest area located in the of the Energy Technologies Building outside the laboratory containing the test room area. The horizontal illuminance in the rest area was approximately 200 lux at 0.8 m height from the floor. Here, the subject was given a copy of the consent form, the questionnaire featuring demographic information, and an overview of the experimental procedure. If the subject had no further questions following the introduction, they were then taken into the test room. In the test room, the detailed experimental steps were explained and a demonstion was provided to ensure the subject was able to carry out the experimental procedure independently.

During the experiments, subjects were seated on a chair located inside the test room, with their back straight and at a height that ensured their gaze was level with the visual tasks as shown in Figure 7(a). The subject remained inside the test room during the experinment, the experimenter remained outside the cubicle and could vocally guide the subject through the procedure.

For each window condition, the subject was asked to complete three tasks, a gap detection task for both achromatic (AA) and chromatic (CA) charts, and a colour naming (CN) task for the chromatic chart. In the gap detection task, the subject was instructed to vocally indicate where they believed the gaps in each ring were according to its cardinal direction (i.e., up, down, left or right). When they could not see the gaps clearly, they were encouraged to guess the answer. For the chromatic Landolt ring chart, an additional colour naming task was also performed. The subject was instructed to indicate the colour of each ring vocally. When they could not recognise the colour of a ring, they were again encouraged to guess the answer.

When the subject seated in the specific position was ready, they informed the investigator and said ‘start’. Then they went through all Landolt rings, telling the gap of each ring on the chart from left to right, and the top to the bottom. They signalled the completion of each task by saying ‘finish’. They were then instructed to change the test chart and start the next session following the same steps.

When completing the tasks under one window condition, the subject was required to fill out a copy of the questionnaire. To record the visual performance of the subject, two parameters were measured in each of the tasks, the rate resonses and the accuracy (freedom from errors) of responses [37, 60]. Both parameters were measured using a portal dictaphone that was mounted near the viewing position of the subject inside the test room. When changing the window conditions, a 2 minute period of relaxation was provided to the subject under normal lighting levels in the foyer. A step by step description of the procedure and estimated time are shown in Table 6.

Table 6. Procedures and estimated time

Time	Activity	Minutes
00:00-00:10	Welcome and introduction	10
00:10-00:12	Demonstration in the test room and make sure subjects understand the procedures	2

00:12-00:18	Subject completes the three Landolt ring tests (random sequence of tasks) and experimenter record responses	6
00:18-00:23	Subject completes the questionnaires and then exits the test room	5
00:23-00:25	Experimenter changes the window type and adjusts the lighting level to 100 lux with the lab assistant Subject has a short rest in the rest area	2
00:25-00:31	Subject enters the test room, and completes the three Landolt ring tests (random sequence of tasks) and experimenter records responses	6
00:31-00:36	Subject completes the questionnaires and then exits the test room	5
00:36-00:38	Experimenter changes the window type and adjusts the lighting level to 100 lux with the lab assistant Subject has a short rest in the rest area	2
00:38-00:44	Subject enters the test room, and completes the three Landolt ring tests (random sequence of tasks) and experimenter records responses	6
00:44-00:49	Subject completes the questionnaires and then exits the test room	5
00:49-00:50	Experimenter records oral feedback about the experiment from subject	1
	Total	
00:00-00:50	Approximate time required	50

To avoid unwanted procedure biases (fatigue and learning), the tasks were randomly assigned to subjects, as well as the window conditions, and the recommended sequence of window types and visual tasks are shown in Table 7.

Table 7. Recommended sequence of windows types and visual tasks

	Three window types		
	Clear	**Bronze**	**Blue**
Subject 1	1st (AA/CA/CN)	2nd (CA/CN/AA)	3rd (CN/AA/CA)
Subject 2	2nd (CA/AA/CN)	3rd (CN/CA/AA)	1st (AA/CN/CA)
Subject 3	3rd (CN/AA/CA)	1st (AA/CA/CN)	2nd (CA/CN/AA)
Subject 4	1st (AA/CN/CA)	3rd (CA/AA/CN)	2nd (CN/CA/AA)
Subject 5	2nd (CN/AA/CA)	1st (AA/CA/CN)	3rd (CA/CN/AA)
Subject 6	3rd (CA/AA/CN)	2nd(CN/CA/AA)	1st (AA/CN/CA)
……	……	……	……
Subject 31	1st (AA/CA/CN)	2nd (CA/CN/AA)	3rd (CN/AA/CA)

4. Analysis methods

Analysis was undertaken on the performance measurements (i.e., time and errors) for each of tasks performed using the Landolt ring charts under the three window conditions, the responses given in the questionnaire surveys under three window conditions, and the demographic information and self-assessment measurements.

SPSS Statistics 23 was used to analyse the experimental data in this study. The time it took subjects to locate the gaps contained in all of the rings, and the number of errors made when specifying a wrong direction or colour for a given ring were selected as the two dependent variables to assess the visual performance of the subjects under in each of the test conditions.

The data collected were tested and found to be non-normally distributed, so a non-parametric Friedman's ANOVA was applied to analyse the differences in visual performance (i.e., speed and time) across the independent variable (i.e., window conditions) to determine whether there is a signficant difference between the three window conditions. Once the statistically significant difference was detected by Friedman's test, a Wilcoxon signed rank was used to isolate the main effect by performing multiple comparison tests [61]. In addition, the effect size of the difference was calculated to indicate the magnitude of the effect of window conditions [62].

5. Results and discussion

Under an illuminance of 100 lux on a vertical target surface (i.e., the visual task), simulated artificial daylight produced through Blue, Bronze and Clear windows created differences in visual performance and subjective appearance. This suggests that the innovative experiment described in this paper, which provides controlled conditions under which test subjects perform a series of visual tasks under these three window conditions is appropriate for exploring the human visual performance.

5.1. Visual performance

Since a non-paramatric Friedman's ANOVA was appiled in the analysis, medium (M_{dn}) values of response time and accuracy were compared. The difference between pairwise comparison is statisitally significant once the p-value is no more than 0.017 with Bonferroni corrections applied (0.05/3=0.017, where 3 is the number of comparisons conducted). However, when p-value is over 0.017, the effect size over 0.2, which also indicates that the difference is statistically significant and cannot be neglected. Therefore, Table 8 shows that, for the achromatic acuity (AA) task, errors made are higher under the Bronze window condition (CCT=4000K) (M_{dn}=2) than under the Clear (CCT=5000K) (M_{dn}=0) and Blue (CCT=7000K) (M_{dn}=1) window conditions. Fotios' and Boyce's [37, 38] studies indicate that different light spectra do not affect human performance on achromatic acuity tasks. However, the study conducted by Berman *et al.* [60], who undertook a test using achromatic Landolt rings, concluded that at low luminance levels, visual acuity is better under higher CCT lighting conditions. It is because the pupil size would reduce, stimulated by higher CCT light, and reduced pupil size improves human eye's visual acuity and contrast sensitivity. In the study presented here, it is suspected that errors in the AA task are not only related to the visual acuity physically, i.e., the response of subjects' eyes, but also to their alertness, arousal and concentration levels when completing each task under the different window conditions. These assumptions are based on previous research which indicates that environments with higher CCT improve alertness [63, 64], and CCTs in the region of 6500 K are beneficial for improving concentration [65].

Table 8. Wilcoxon signed-rank paired test between errors recorded in Achromatic Acuity (AA) tasks under three light conditions with significant results

Conditions	M_{dn} (IQR)	M_{dn} (IQR)	Positive	Negative	Ties	Effect Size (r)
Bronze vs. Clear	2 (5)	0 (5)	16	7	8	0.32**
Bronze vs. Blue	2 (5)	1 (5)	12	3	16	0.25*

**means there is a statistically significant difference between the pairwise comparison and a non-negligible effect size (>0.2) at the same time; *means there is no statistically significant difference between the pairwise comparison, but a non-negligible effect size (>0.2)

In terms of CA tasks, no significant difference (p-value > 0.017) was detected across the three window conditions. However, when comparing the errors made by subjects, shown in Table 9, between achromatic (AA) and chromatic acuity (CA) tasks under each condition, subjects present significantly more errors in the CA task than in the AA task under the clear and Blue window types. Under the luminous condition produced by the Bronze window, the effect size detected a non-negligible difference as well. It likely that the poorer contrast of the coloured Landolt rings in CA test as compared with the black rings in the AA test, as illustrated in Table 3, increases the difficulty of discrimination.

Table 9. Wilcoxon signed-rank paired test between errors recorded in Achromatic (AA) and Chromatic Acuity (CA) tasks under three light conditions with significant results

Conditions	M_1 vs M_2	M_{1dn} (IQR)	M_{2dn} (IQR)	Positive	Negative	Ties	Effect Size (r)
Clear	AA vs CA	0 (5)	2 (7)	3	15	13	-0.42**
Blue	AA vs CA	1 (5)	3 (6)	5	16	10	-0.30**
Bronze	AA vs CA	2 (5)	3 (6)	7	19	5	-0.21*

**means there is a statistically significant difference between the pairwise comparison and a non-negligible effect size (>0.2) at the same time; *means there is no statistically significant difference between the pairwise comparison, but a non-negligible effect size (>0.2)

In the CN task, colour discriminations of red, green and blue did not show a significant difference across three window conditions. However, it is worth noting that errors where they did occur were recorded between green and blue. Almost every subject experienced problems distinguishing these two colours, especially at small ring sizes. This is probably because of the similar spectral reflectance of green and blue rings, shown in Figure 8, which increases the difficulty for human eyes to discriminate between reflected light within similar wavelength ranges.

Time spent on completing tasks indicated two issues in this study: 1) productivity under certain conditions 2) reliability of completing different tasks. Figure 9 indicates that subjects almost spent equal time to do the same tasks across the three windows conditions (p-value > 0.017, difference is non-significant). This means that Blue and Bronze windows have the potential to maintain productivity. However, when the difficulty of task level was increased, i.e., comparing the time spent on achromatic and chromatic acuity tests, only the Blue window presented a non-significant difference between the two tasks. This means that subjects could maintain their speed of completing more challenging tasks under the Blue window condition (i.e., higher CCT of 7000 K). This also means that higher CCT environment is beneficial to maintain the efficiency of task performance, a result that is consistent with previous research [63, 64].

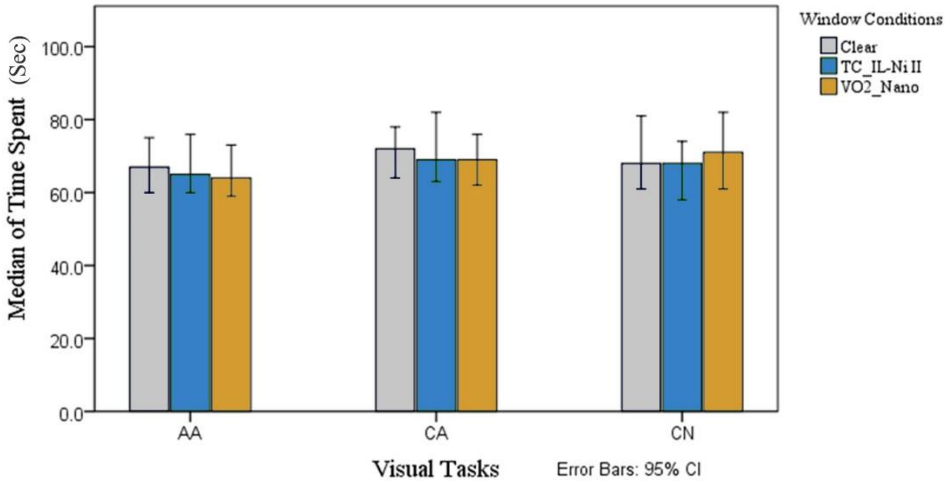


Figure 9: Comparisons between medians of time spent (units are seconds) in the achromatic acuity (AA), chromatic acuity (AA), and colour naming (CN) tasks under the three window conditions, respectively. Error bars show the 95% confidence intervals

5.2. Subjective assessment

Table 10 presents a comparison of the answers from the questionnaire with significnat results indicated. According to the three paired significant difference analysis obtained for Q4 (which explores discrimination of colour temperatures), the subjective assessment shows that even in the low illuminance environment (100 lux) subjects could discriminate the variation of CCT (4000-7000 K) caused by the chromic windows. The Blue window condition was perceived as a more unnatural rendition of coloured targets inside the room, especially compared with the clear window conditions (Q5). The Blue window was also found to be less comfortable and acceptable than the Bronze and Clear window conditions (Q15 and Q16). Additionally, subjects indicated that they would like to spend a long time working under the Bronze window condition compared with the Blue one. Previous research also supports this conclusion, which indicates that an environment with warmer CCT is more desirable [1, 27, 36, 66].

Table 10. Wilcoxon signed-rank paired test between errors recorded in Achromatic and Chromatic Acuity tests under three light conditions with significant results

Questions	Conditions (M_1vsM_2)	M_{1dn} (IQR)	M_{2dn} (IQR)	Positive	Negative	Ties	Effect Size (r)
	Blue vs. Clear	2 (1)	2 (1)	5	16	10	-0.28*
Q4	Bronze vs. Clear	3 (2)	2 (1)	15	4	12	-0.35**
	Bronze vs. Blue	3 (2)	2 (1)	20	4	7	-0.45**
Q5	Blue vs. Clear	2 (1)	3 (1)	3	13	15	-0.33**
Q15	Blue vs. Clear	2 (0)	2 (1)	5	13	13	-0.27*
	Bronze vs. Blue	2 (1)	2 (0)	15	3	13	-0.28*
Q16	Blue vs. Clear	2 (1)	2 (1)	2	13	16	-0.30**

**means there is a statistically significant difference between the pairwise comparison and a nonnegligible effect size (>0.2) at the same time; *means there is no statistically significant difference between the pairwise comparison, but a non-negligible effect size (>0.2)

6. Conclusions

Through the use of an innovatively designed test room, i.e., a mock-up office cell lit by an artificial window, human response to chromatic glazing was investigated. In this test room, subjects completed both objective and subjective tests. Statistical analysis (Friedman's and Wilcoxon signed rank) detected that a Bronze window condition (in this paper representing a VO_2_Nano TC window with CCT= 4000K) caused more errors in achromatic acuity tests than a Blue window condition ((in this paper representing a TC_IL-Ni^{II} TC window with CCT= 5000K) and a clear window condity (in this paper representing conventional glazing transmitting daylight with a CCT of 7000K), 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. These results were all consistent with previous studies, which suggest that the experimental system described in this paper is appropriate for conducting studies of this type.

Additionally, compared with the methods applied in the previous studies, the advantages of this method are as follows:

1) It simulates a daylit environment effectively through appropriate selection of a light source for integration into an artificial window.

2) Luminous conditions, including illuminance levels and the correlated colour temperature are flexible and easy to adjust as compared with the unstable conditions observed when conducting experiments under natural daylight.

3) The size of the mock-up office is suitable for subjects to access and undertake visual tasks.

4) The experimental method is economic and sustainable making it suitable for use in experiments on other advanced or smart window systems.

In future studies, different levels of lighting will be explored using this experimental apparatus, in order to further validate this innovative method and explore human response to luminous environments affected by TC windows. In addition, other aspects of performance, such as sustained attention and fatigue will be assessed with the aim of providing more guidance for developing TC materials that meet the requirement of human visual and non-visual comfort.

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