Development of an Adaptive Façade for Visual Comfort, Daylight and Thermal Control Element

Runqi LIANG

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Abstract

Thermochromic (TC) windows were developed as a passive building component to improve indoor comfort and building energy conservation in place of traditional clear glazing systems. TC materials enable a spectrum-dependent regulation of solar radiation through windows stimulated by heat. When the temperature is higher than its transition temperature, less solar radiation, primarily in the near infra-red (NIR), will be admitted inside the building, reducing over-heating on hot days. Meanwhile, the TC materials tint to bluish or brownish appearance along with the transition. Most research about the commonly studied Vanadium dioxide (VO_2) based TC windows was focused on fabrication methods and properties improvement of VO_2 based materials, and a few numbers of studies investigated their energy performance when applied in buildings. Therefore, this research conducted a thorough investigation of TC windows applied in buildings, covering characteristic of TC windows, energy efficient, daylighting performance, and human response affected by different types of TC windows. Both simulation and experimental methods were carried out to explore the potential of TC windows. That aim is to provide a detailed guidance for the development of TC materials that are more flexible and acceptable to use in a practical building. The comprehensive analysis mainly consists of four parts: 1) simulation work on the evaluation of TC windows on energy efficient and daylighting, also the window size effects under five typical climates; 2) further evaluation of the potential of developed TC windows with enhanced capability of adjusting visible and NIR transmittance individually or cooperatively; 3) experimental investigation of the research hypothesis that TC tinted window has no effect on the human visual performance and subjective sensation, in a test room cubicle with a low level of simulated daylit (100lux); 4) further experimental investigation to detect the acceptance range of tinting for different windows at an indoor comfort illuminance level (350 lux). Findings show that compared with reducing the transition temperatures, improving capability of adjusting visible or NIR transmittance is more effective to improve both daylighting and energy performance. TC windows are more energy efficient when applied in buildings with large glazing area under cooling dominated climates. However, dynamic reduction of visible transmittance is required to decrease the risk of visual discomfort caused by over daylighting, especially for cities with lower solar altitude. Under a dark illuminance, bronze tinted TC windows were preferred subjectively, however, subjects had better visual performance under blue tinted TC window conditions. Sustained attention (i.e., focus on an activity for a long period of time) was not affected by TC window conditions (i.e., with correlated colour temperature (CCT) ranging from 3300 to 11000K), but further tinted bronze window was subjectively considered to improve concentration. Therefore, adjustment of visible transmittance is highly recommended for warm tinted TC windows. Simulation and lab experiment might have some limitation on this study, further work is suggested by carrying out further validation and employing more samples.

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Liang R., Wu Y., Wilson R. The effects of optical properties on VO_2-based thermochromic smart windows applied in a typical office, 8th International SOLARIS conference, London, UK, 2017

Liang R., Wu Y., Wilson R. Thermal and visual comfort analysis of an office with thermochromic smart windows applied. CISBAT, Lausanne, Switzerland, 2015

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Nomenclature

$E_{\lambda b}$	Spectral distribution of radiation emitted by a blackbody
E_b	Total radiation emitted per unit area by a blackbody
h	Planck's constant
k	Boltzmann's constant
λ	Wavelength
σ	Stefan-Boltzmann constant
T	Temperature of a blackbody in K
λ_{max}	The wavelength corresponding to the maximum radiation of a blackbody
τ_λ	Wavelength-dependent transmittance
ρ_λ	Wavelength-dependent reflectance
α_λ	Wavelength-dependent absorptance
ε_λ	Wavelength-dependent emittance
ε_i	Emissivity of face i
k_i	Conductance of glass layer i
h_o	Outside, inside air film convective conductance, W/m^2K
T_o	Indoor air temperatures, K
E_o	Exterior, interior long-wave radiation incident on window W/m^2
θ_i	Temperature of face i, K
S_i	Radiation (short-wave, and long-wave from zone internal sources) absorbed by face i, W/m^2
I_{bm}^{ext}	Exterior beam normal solar irradiance W/m^2
I_{dif}^{ext}	Exterior diffuse solar irradiance on glazing W/m^2
I_{sw}^{int}	Interior short-wave radiation (from lights and from reflected diffuse solar) incident on glazing from inside W/m^2
I_{lw}^{int}	Long-wave radiation from lights and equipment incident on glazing from inside W/m^2
A_j^f	Front beam solar absorptivity of glass layer j
$A_j^{b,dif}$	Front and back diffuse solar absorptivity of glass layer j
φ	Angle of incidence
$I_{\lambda sun}$	Emission spectrum of the sum

$\varepsilon_{material}$	Emission of the material at normal ambient temperature
$T_{\lambda\ sol}$	Full-spectrum solar direct transmittance
$R_{\lambda\ sol}$	Full-spectrum solar direct reflectance
S_{λ}	The relative spectral distribution of the solar radiation
C	Contrast
L_b	Background luminance in cd/m^2
L_t	Target luminance in cd/m^2
R	The sum of the ranks
p	Statistical significance
F	The test statistic
η^2	Eta-squared/ effect size
IQR	inter-quartile range
N	Number of participants
χ^2	Chi-square, test statistic
r	Pearson's correlation coefficient, effect size for Wilcoxon singed-rank
Z	Z-score
M_{dn}	Median
df	freedom
CCT	Correlated colour temperature

Chapter 1

Introduction

1.1 Background

Over the past decades, there has been an increase in public awareness with regards to the importance of energy saving and effect of the quality of indoor environments on occupants' health and comfort. Energy consumption from buildings accounts for a significant proportion (approximately 40%) of the world's primary energy consumption [1]. In developing countries such as China, the proportion was predicted to increase from 28% to 35% by 2020 [1]. The greenhouse gas emissions caused by using fossil fuels in buildings is one of the main causes of global warming. Therefore, energy conservation has become a focus of energy policies and decision making for architectural design [2, 3]. In a typical domestic resident house in U.S., heating, cooling, lighting and hot water contribute to approximately 60% of total energy consumption, meanwhile, a commercial building consumes less heating, but more energy on cooling and lighting by around 15% [4].

Window systems play a unique role as the transparent component within a building which provides daylight, views to the external environment and fresh air to the occupants. Notwithstanding, they are considered to be thermally weak, as around 60% of energy loss can be caused by conduction, convection, and radiation through the windows [5]. Therefore, designing and selecting an optimal window system is an essential strategy for maximizing the benefits of occupant comfort and building energy efficiency [6]. Many elements determine the selection of windows, such as the building type (i.e. domestic / non-domestic), climates and so forth. Window types available to choose from include low-cost single gazing, highly insulated double/triple glazing, windows with different solar control functions (low-e glazing, high reflective metallic glazing), and innovative smart windows that dynamically control the transmitted solar radiation.

Thermochromic (TC) smart windows have the simplest structure among the four types of chromogenic windows (i.e., electrochromics, photochromics, gasochromics and thermochromics) [7]. Under the stimuli of heat, TC materials have the features of reversibly changing optical properties responding to temperatures, meanwhile, along with tinting to alternative colours. Transition temperature (Tt), visible transmittance (τ_{vis}) and near infrared (NIR) transmittance (τ_{nir}) are the three main elements that influence the performance of TC windows. Vanadium Dioxide (VO_2) as one of the most widely studied TC materials, has the features of reducing τ_{nir} when its temperature is rising above Tt, and meanwhile, have an almost constant τ_{vis}. This means that VO_2-based TC windows could block undesired solar heat gains, but admit visible spectrum to supplement lighting levels [8]. Additionally, another type of TC with Iron-liquid complex materials was developed for tunable visible transmittance [9]. This means that it has potential to reduce visible radiation at the temperature above transition temperature, when glare appears.

A variety of studies on VO_2 TC materials focused on the development of materials, i.e., fabrication methods, reducing transition temperature, enlarging the reduction of NIR transmittance while keeping a high visible transmittance [8, 10, 11]. Although these improvements of TC properties by chemical approaches were proposed to meet the requirement of energy efficient building component, studies were rarely carried out to explore their performance during application in buildings. Only a few studies were conducted by Saeli *et al* [12, 13], Ye *et al* [14, 15], Gao *et al* [10], Hoffmann *et al* [16], which indicated that buildings in hot climates were suitable for applying VO_2 TC windows, and 19.9% reduction of cooling load could be achieved. Besides the TC properties, climatic conditions (e.g., solar radiation, ambient temperatures), and building fenestration designs (e.g., area of window surface) affect the energy and daylighting performance of the building with TC windows installed. However, no current studies conducted a comprehensive quantitive research to define the exact characteristics of climates and fenestration design that are appropriate for TC application. In addition, since structures of TC films are simple, daylighting distribution affected by TC windows was neglected [7]. Oversupplied daylighting is a common issue that should be addressed. TC materials with tunable visible transmittance have the potential for glare control.

During transition, almost all TC materials would tint to darker state or switch to other colours. VO_2 based materials are mainly tinted to be brown/yellow (i.e., pure VO_2), and green/blue (i.e., metal doped VO_2). The Iron-liquid based TC materials have the similar performance and also colour after transition. Therefore, daylighting filtered by tinted TC glazing is possible to change their spectrum distribution according to the spectral transmittance of TC glazing applied, resulting in different correlated colour temperature (CCT) of the indoor luminous environment [17, 18]. Meanwhile, CCT is one of the essential factor that influence both visual and non-visual senses of human beings [19-21]. The effects of TC windows on visual performances (i.e., achromatic acuity, chromatic acuity, and colour discrimination), sustained attentions, and subjective assessments have not yet been studied. These are important for TC window developments and also application for buildings.

1.2 Aims and Objectives

In this study, a comprehensive analysis of the application of TC windows in an office room, representing the commercial buildings which has increasing requirement for fenestrations, was conducted including energy and daylighting performance through building simulations by EnergyPlus modelling, and human visual response through lab experiments. Simulation methods were validated by comparing outputs with previous measured results. In the building simulation, the energy saving potential of the selected TCs at different climatic conditions, daylighting availability, as well as the effects of TC window to wall ratios were discussed. Moreover, in-depth discussion was also carried out to explore the potential development of various TC materials for better daylight and solar heat gain controls. That aims to provide suggestions for adjusting thermochromic properties according to different climates requirements to achieve energy efficient design for buildings and also a comfortable environment for both thermal and daylight.

Based on the tinting properties of TC windows, experiments were designed to explore the effects of the typical TC windows applied in the simulation part on visual acuity, attention and subjective assessment when compared with a normal clear window. Two illuminance levels were selected for the experimental tests: 1) Under a threshold low illuminance level of 100lux simulated daylit environment to explore visual performance supra-threshold affected by TC windows; 2) under a comfort illuminance level of 350lux simulated daylit environment to explore sustained condition and acceptable threshold of TC tinting. Overall, this study was proposed to provide a detailed guidance for the future development of TC windows, realizing their potential application in practical buildings.

1.3 Thesis outline

Chapter 1. Introduction: presents an overview of the thesis contents, including a brief introduction of current fenestration development, the requirement of innovative fenestration devices for energy efficient building design, and the aims and objectives for this study.

Chapter 2. Review of literature: shows a comprehensive literature review in advanced fenestrations, covering the fundamental of the solar spectrum, current development of various windows, TC windows including its working principles, fabrication methods, the main parameters determining the window performance.

Chapter 3. Evaluation of the thermal and optical performance of Thermochromic windows: explores the potential of thermochromic glazing under various climatic conditions by modelling the energy and daylight performance of a typical office room with five different thermochromic glazing types (i.e. with varying transition temperatures ranging from 20°C to 41.3°C, solar transmittances from 0.412 to 0.690) simulated under five climatic conditions in China, representative of different climate zones. A comprehensive analysis was conducted, including: a study of the thermal and optical behaviours of the selected thermochromic glazed windows; energy use for heating, cooling and artificial lighting of the selected office; and effects of window-to-wall ratios on office performance under the selected climatic conditions.

Chapter 4. Further evaluation of thermochromic windows for energy efficient design and daylight control: according to the findings in chapter 3, two TC windows (VO_2_Nano, and TC_IL-Ni^{II}) were selected for further studies. Different scenarios were carried out to explore the best TC window performance through varying the transition temperature of the selected TCs, improving the visible and NIR transmittance, and different combination of the TC window films.

Chapter 5. Human response to tinted TC windows: An innovative test room cubicle lit by an artificial window was designed to investigate whether the visual responses given by test participants are influenced by different TC glazing containing different colours. Especially, the study aims to investigate visual responses when carrying out both objective tasks (i.e., achromatic acuity, chromatic acuity and colour discrimination) and subjective assessment under different coloured TC windows.

Chapter 6. Human response to potential developed tinted TC windows: Based on the experimental findings from chapter 5, another controlled experiment was conducted, exploring sustained attention, achromatic acuity, colour discrimination, and subjective assessment affected by further tinted TC windows containing darker colours (i.e., more reddish or bluish tinting) under a comfort illuminance level. It aims to find out the acceptable range of TC tinting.

Chapter 7. Conclusions: this chapter summarised the results of chapters 3, 4, 5, and 6. Also, it discussed the potential development of TC materials that suitable to be applied in practical buildings, in terms of energy conservation, daylighting performance and visual comfort. Finally, limitations and future works of this study were identified.

Chapter 2

Literature Review

-Energy Efficient Windows

2.1. Basics of solar radiation and window performance

In this Chapter, principles of spectral solar radiation and their interaction with windows (transmittance, reflectance, absorptance and emissivity) are reviewed to fundamentally understand the performance of windows. Based on the review about traditional solar control window and dynamic smart windows, the thermochromic smart window was selected for investigation due to its simple structure, easy fabrication, and automatic change of states without extra energy. This chapter aims to comprehensively understand the state of art of thermochromic smart windows and find out the research gap in this field.

2.1.1. The spectrum of solar radiation

A blackbody is an ideal concept, which can absorb all incident radiation, and simultaneously emit the same amount of energy as thermal radiation. Thermal radiation is the electromagnetic wave within the spectral range from 0.2 to approximately $1000\mu m$, and is emitted by all substances with a temperature above absolute zero. The spectral distribution of radiation emitted by a blackbody is calculated by Planck's law [22]

$$E_{\lambda b} = \frac{2\pi h C_o^2}{\lambda^5[\exp\left(\frac{hC_o}{\lambda kT}\right)-1]} \qquad \text{Equation [2.1]}$$

Where h is Planck's constant, and k is Boltzmann's constant. The group $2\pi h C_o^2$ is called Planck's first radiation constant, and $\frac{hC_o}{\lambda kT}$ is Planck's second radiation constant, they are given the symbols C_1 and C_2, respectively, and recommended values are C_1= 3.7405× 10^8 W$\mu m^4/m^2$ and C_2 =14, 387.8μmK.

Integrating the radiation of an overall wavelength that Planck's law informed, the total radiation emitted per unit area by a blackbody (i.e., the intensity of radiation) is given by Stefan-Boltzmann law.

$$E_b = \int_0^{\propto} E_{\lambda b} d\lambda = \sigma T^4 \qquad \text{Equation [2.2]}$$

Where σ is Stefan-Boltzmann constant, and recommended value is 5.6697×10^{-8} W/m^2K^4. T is the temperature of a blackbody in K.

Additionally, Wien's displacement law indicates the relationship between the wavelength corresponding to the maximum radiation of a blackbody λ_{max} and its temperature *T*:

$$\lambda_{max} T = 2897.8\ \mu m K \qquad \text{Equation [2.3]}$$

From equation 2.2 and 2.3, it can be estimated that the increase of blackbody temperature results in the higher intensity of energy radiation, at the peak intensity of energy achieved at a lower wavelength.

The sun is an approximate blackbody since solar spectrum as well close to a blackbody spectrum. The sun has an effective blackbody temperature of 5777K, which means that a 5777K blackbody radiates the same amount of energy as that of the sun. It is necessary to mention that the wavelength range of solar radiation is limited to 0.25 to 3 μm. Therefore, three main intervals were classified: 1) Ultra-violet (UV) (0.25-0.38 μm), which causes skin damage, also help produce Vitamin D; 2) visible (0.38-0.78 μm), which human eyes are sensitive to; 3) near infrared (NIR), which is the main cause of solar heat.

2.1.2 Window performance interacting with solar radiation

When a window exposed to incident solar radiation, their interaction performs in three ways: incident solar radiation can transmit through the glazing, and meanwhile be reflected, and absorbed by glazing. According to an expression of energy conservation, the relationship of the three interactions at each wavelength is required to be:

$$\tau_\lambda + \rho_\lambda + \alpha_\lambda = 1 \qquad \text{Equation [2.4]}$$

Where, τ_λ, ρ_λ, and α_λ are wavelength-dependent transmittance, reflectance, and absorptance, respectively. Kirchhoff's radiation law present that, the energy emitted by the materials is equal to energy absorbed, therefore:

$$\alpha_\lambda = \varepsilon_\lambda \qquad \text{Equation [2.5]}$$

Where, ε_λ is wavelength-dependent emittance, however, because average and overall absorptance and emittance are often given for different materials, the values differ from each other. For example, the absorptance of material heated by solar radiation is weight by the solar spectrum (see Equation (2.6)), however, the emittance of the material is weight by emission of the material at normal ambient temperature, which depends on the material temperature and wavelength of emitted energy (see Equation (2.7)).

$$\alpha_{sun} = \frac{\int_0^\infty \alpha_\lambda I_{\lambda sun}(\lambda) d\lambda}{\int_0^\infty I_{\lambda sun}(\lambda) d\lambda} \qquad \text{Equation [2.6]}$$

$$\varepsilon_{material} = \frac{\int_0^\infty \varepsilon_\lambda(\lambda,T) E_{b\lambda}(\lambda,T) d\lambda}{\int_0^\infty E_{b\lambda}(\lambda,T) d\lambda} \qquad \text{Equation [2.7]}$$

Where, $I_{\lambda sun}$ is emission spectrum of the sum, and $E_{b\lambda}(\lambda, T)$ is the emission of a blackbody with the same temperature of the material.

For the full-spectrum solar direct transmittance ($T_{\lambda sol}$) and reflectance ($R_{\lambda sol}$) of the glazing, it is calculated by the following formula:

$$T_{\lambda\, sol} = \frac{\sum_{\lambda=300nm}^{2500nm} S_\lambda \tau_\lambda \Delta\lambda}{\sum_{\lambda=300nm}^{2500nm} S_\lambda \Delta\lambda} \qquad \text{Equation [2.8]}$$

$$R_{\lambda\, sol} = \frac{\sum_{\lambda=300nm}^{2500nm} S_\lambda \rho_\lambda \Delta\lambda}{\sum_{\lambda=300nm}^{2500nm} S_\lambda \Delta\lambda} \qquad \text{Equation [2.9]}$$

Where, S_λ is the relative spectral distribution of the solar radiation, which depends on air mass (AM) e.g., AM=1 stands for the sun is being at the angle of approximately 60° from the horizon. $\Delta\lambda$ is the wavelength interval.

Within the application of windows , three main aspects should be taken into account: 1) the regulation of heat transfer between indoor and outdoor environment, i.e., insulation properties; 2) the regulation of solar spectrum, it is often significant to limit the transmitted solar radiation within a certain wavelength (i.e., NIR spectrum of 0.78-2.5 μm) radiation that might result in interior overheating), while keep desirable daylighting (i.e., human eyes sensitive spectrum of 0.38-0.78 μm) availability and good view through the windows. 3) For the tinted window, visual comfort of occupants is an additional issue to be measured. In order to improve window performance, increase energy conservation and meet the requirement of human visual and thermal comfort, various window technologies were developed in recent decades. In the following sections 2.2 and 2.3, static and dynamic solar control given by different windows are introduced.

2.2 The static solar control window

Changing the composition of glazing and coating on the surface of glazing both affects the spectral selectivity of windows [23]. By changing the additives during the fabrication, glass will be tinted as different colours, such as grey, bronze, blue, green, etc. E.g. green tinted glass is obtained by reducing iron oxide (Fe_2O_3) contents, compared with standard and water white glass (see Figure 2.1) [24]. It effectively reduces the transmittance of NIR spectrum and has a similarly visible transmittance as standard glass. The reduction of NIR transmittance is achieved by absorbing undesirable NIR solar radiation. It means that the absorbed solar energy could heat up the glass and emit into both interior and exterior space in the form of longwave radiation, diminishing the solar heat gain decrease caused by lowering transmitted NIR radiation.

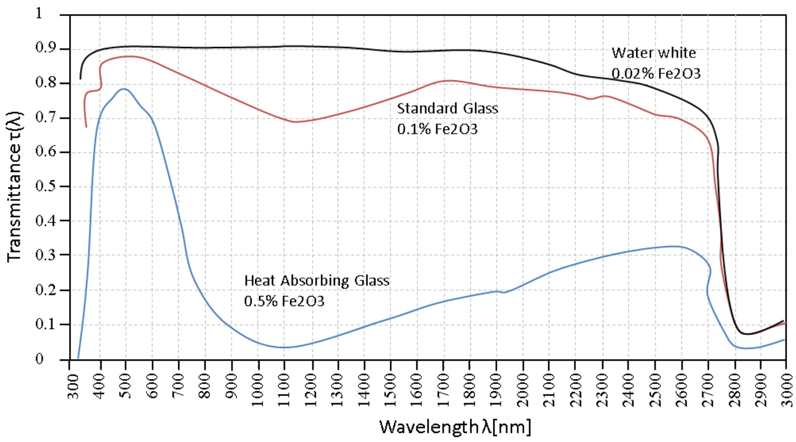


Figure 2.1: Spectral transmittance of green tinted glass and clear glass

Therefore, low-emittance (low-e) coating was developed to modify this shortcoming of tinted glass. Figure 2.1 illustrates three generations of low-e windows: high, moderate and low solar gain low-e coatings, depending on the solar control in NIR spectrum. Instead of absorbing NIR spectrum, low-e coating reflects the undesirable NIR solar radiation (i.e., $780\text{nm} < \lambda < 2500\text{nm}$) and long-wave radiation (i.e., $\lambda > 2500\text{nm}$), thus, controlling the solar heat throughput and reduce indoor heat loss (i.e., maintaining a low U-value, well thermal insulated) passively. A standard glass has an emissivity of 0.840, while the minimum emissivity of low-e coating is 0.013 [25, 26]. It means that only 1.3% of solar energy incident on the glazing surface with low-e coating can be emitted. In the window configuration, solar control coatings are used to install on the inner surface of the glass pane outside of a multi-layered window system. The first generation, high solar gain low-e was designed for heating demand period, admitting full spectrum solar radiation and reduce heat loss by reflecting long-wave radiation back in the room. While the low heat gain low-e coating can be used in cooling demand period, blocking unwanted solar heat and maintaining a low U-value.

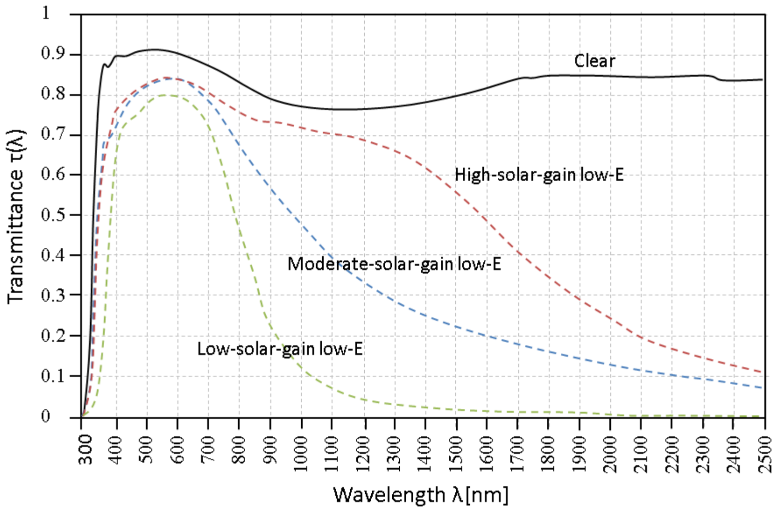


Figure 2.2: Spectral performance of different low-e glazing (source: http://www.commercialwindows.org/lowe.php).

2.3. The dynamic solar control window

Traditional solar control windows are static and suitable for specific climatic conditions. To control solar spectrum dynamically, and improve flexibility and energy efficiency, switchable solar control technologies were widely studied in recent decades. The family of switching devices including suspended particles devices, polymer-dispersed liquid crystal devices, micro-blinds, and chromogenic technologies. Among that, chromogenic technologies are more intended to be applied in buildings, since they are able to adjust transmitted solar radiation dynamically, having the potential to improve both energy performance and daylighting distribution.

Depending on the stimulus, chromogenic technologies are classified into 1) Electrochromics, the stimulus is electrical voltage or current; 2) Photoelectrochromics, the stimulus is light; 3) Gasochromics, the stimulus is gas; 4) Thermochromics, the stimulus is heat/temperature. In this section, a brief introduction of the four types of chromogenic technologies is presented.

2.3.1. Electrochromics

Electrochromic (EC) materials are the maturely studied chromogenic technologies. In the late 1960s, Deb and co-workers first discovered the properties of electrochromism in WO_3 and MoO_3 [27]. A typical EC device consists of five layers, as is illustrated in Fig.2.3. The five layers are arranged as: a transparent electronically conductive film deposited on glass; An electrochromic film (usually WO_3); An ion conductor (electrolyte) in liquid, gel, or solid state; An ion storage film; and a second transparent conductive film.

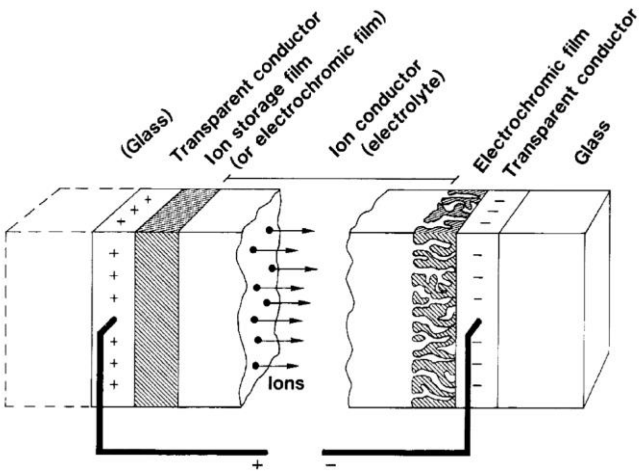


Figure 2.3: Structure and operation of a typical electrochromic device [28]

When a voltage is applied across the two electrodes, positive protons depending on the electrolyte type are forced to leave the electrolyte and go to the active electrochromic film. The electrons are also injected from the external circuit into the layer to keep charge balance, this process changes its electronic density and results in colouration of the material. When the voltage polarity is reversed, the ions and electrons will move in the opposite directions and back to the initial position so that the material will be clear again [29, 30].

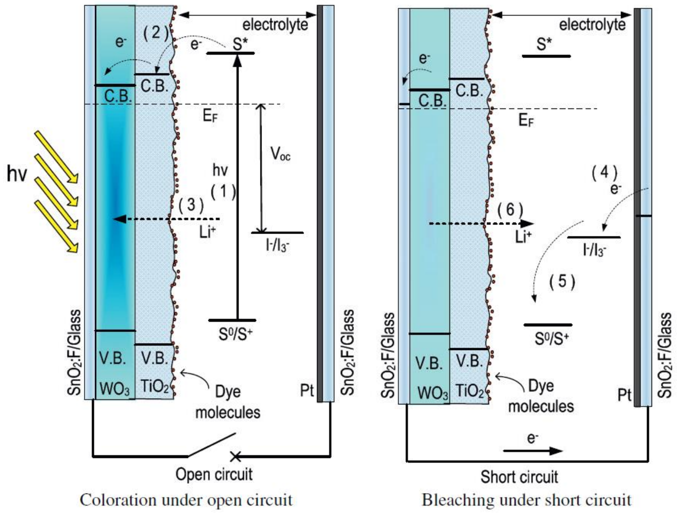
In the USA, it is reported that 4.5% of energy saving could be achieved annually by using EC windows in both commercial and residential buildings [31]. Lawrence Berkeley

National Laboratory (LBNL) researched the large-area EC windows applied in commercial buildings, results show that EC windows saved 6-24% of light energy, and meanwhile, it is limited to be applied in cold winter periods because of its slow switching speed [32]. When compared with large-area single glazing, EC windows are proposed to have energy conservation of 54% in heating-dominated area, and 52% in cooling-dominated area, the expected lifetime is 25 years [7, 33].

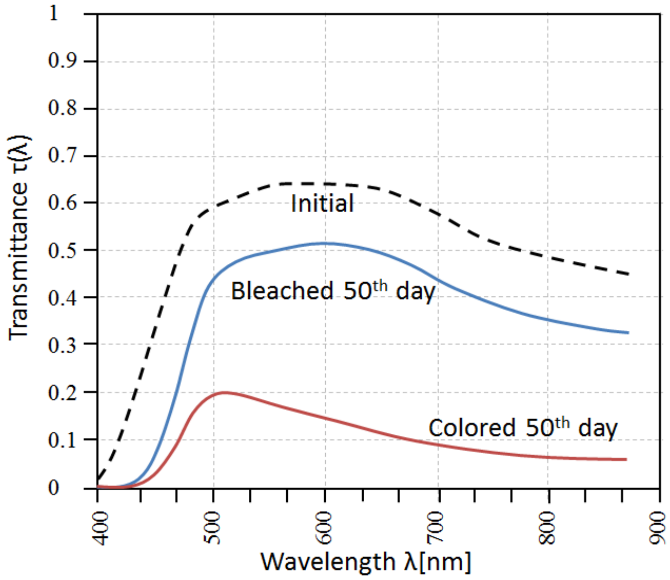
2.3.2 Photo (electro) chromics

A photoelectrochromic (PEC) device combines the function of photovoltaic (PV) and electrochromic (EC) synergistically [34]. A typical configuration includes: a glass coated with a transparent conductive oxide (such as SnO_2: F or indium tin oxide); an EC layer of optical quality (usually WO_3); a nano-structured wide band gap semiconductor film sensitized by an appropriate dye (usually TiO_2); an electrolyte with high ionic and low electronic conductivity that contains a redox couple (such as I^-/I^{3-}), and Li ions; a counter electrode consisting of a transparent conductive oxide with a thin Pt layer.

As shown in Figure 2.4, incident light activates the dye molecules on TiO_2 from the ground state to an excited state: electrons with full energy are injected into the conduction band of TiO_2, and then transfer in the WO_3 conduction band. Lithium (Li) icons site into the WO_3 layer to keep the charge balanced. Coloration is caused by Li+ moving process under open circuit. Under short circuit, I^{3-} ions at the counter electrolyte are reduced by electron flow through the external circuit, so the WO_3 film is bleached [35]. For PEC glazing, the exploration of material stability presents that its transmittance is decreasing day by day. On the 50th day, the change of visible transmittance is from 50% (bleached) to 20% (coloured) [36]. PEC is a passive device without extra power. However, because of its low visible transmittance and poor stability, further improvement is required before its application in practical.



(a) PEC working principle



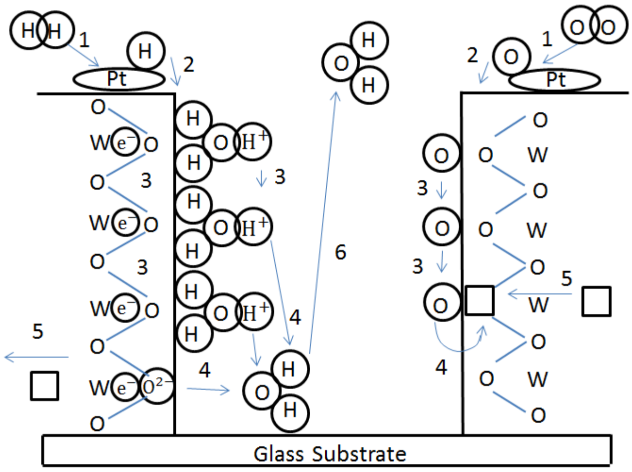
(b) spectral transmittance of PEC

Figure 2.4: Working principle (a) and spectral transmittance (b) of photoelectrochromic [7, 36]

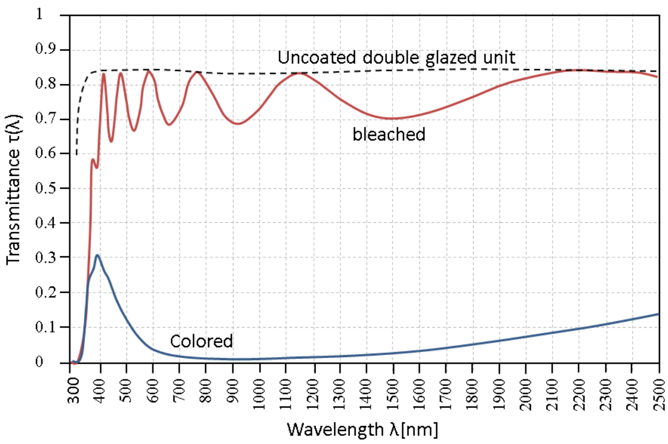
2.3.3. Gasochromics

By changing exposure to diluted H_2 and O_2 gases, Gasochromic (GC) film enables a reversible switch of its optical transmittance [37]. Its layers form the GC film including: a Pt thin film coating; a porous, columnar film of WO_3 no more than 1μm; and a glass substrate. Figure 2.5 (a) illustrates the working principle of a GC device, when the WO_3

film exposes to a low concentration of H_2 (below the combustion limit of 3%) in a carrier gas, it tints to blue. While O_2 is fluxing in, the WO_3 film is bleached to the original transparent state. [38] Figure 2.5 (b) shows an optical properties of GC glazing, visible transmittance is nearly 80% at bleached state, which is similar to uncoated double glazing, and it is reduced to 30% at tinted state [38]. Compared with single glazing, 28.4% decrease of HVAC loads was obtained in a building in Shanghai [39].



(a) GC working principle



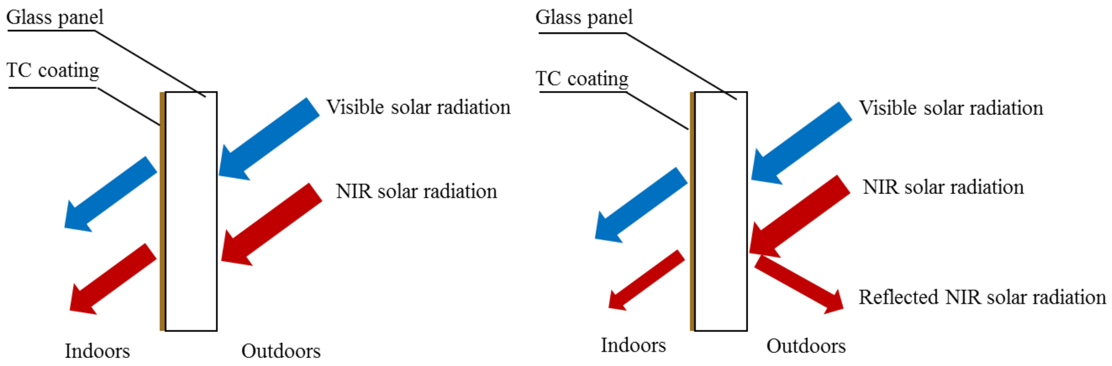
(b) spectral transmittance of GC

Figure 2.5: Working principle and spectral transmittance of gasochromic glazing [38]

2.3.4. Thermochromic

Thermochromic (TC) materials have the characteristics of undergoing a reversible structural transformation, which affects the optical properties simultaneously, and this transformation depends on temperature variation. A variety of materials perform thermochromism including inorganic, organic and polymers. For example, some metal oxide such as Fe_3O_4, NbO_2, Ti_2O_3, V_2O_3, VO_2 and TiO_2 all present TC properties [16]. Among them, Vanadium dioxide (VO_2), firstly reported in 1959, is one of the most widely studied and promising reversible TC materials [40]. As is show in Figure 2.6 Each VO_2 based material has its own transition temperature (Tt), VO_2 performs as a semiconductor admitting most of the full spectrum solar radiation transmitted at the temperature lower than Tt (S-state/clear state); and it performs as a semi-metal with higher reflectivity within NIR spectrum, when its temperature is above Tt (M-state/tinted state) [7, 41, 42]. During the transition, colours of the TC film slightly change as wall.

The pure VO_2 film has a transition temperature of 68°C, and peak visible transmittance is approximately 40%. With the purpose of developing VO_2 material to be energy efficient when applied in building fenestration, there are three issues to be addressed: 1) decrease Tt to a proper level; 2) improve visible transmittance (τ_{vis}); 3) enlarge the change of NIR transmittance (τ_{nir}) before and after transition. Various fabrication methods were studied to achieve the improvements, which was introduced in the following section 2.4, as well as their performance. Compared with the other three chromogenic devices, TC materials are simpler in mechanism, and passive switchable, which has potential to be used in window glazing for energy efficiency. Therefore, this study was focused on TC materials.



(a) Clear state (T<Tt) (b) Tinted state (T>Tt)

Figure 2.6: Schematic representation of thermochromic material applied as a smart window coating

2.4. Thermochromic materials and their performance

For decades, besides VO_2 based thermochromic materials, studies were also carried out for complex and polymer materials with thermochromic properties. Depending on their changes in optical properties, the TC materials can be classified into three types:

Type 1) a large reduction of NIR transmittance, and a little decrease of visible transmittance during the transition from clear to tinted states, e.g. VO_2 based TC material [13];

Type 2) a large reduction of visible transmittance, and little variation of NIR transmittance, e.g., Ionic Liquid-Ni^{II} complexes [9];

Type 3) Simultaneous reductions of visible and NIR transmittance, e.g., Suntuitive dynamic glass [43].

This section provided an introduction to overall studies about fabrication, thermochromic properties, and performance of VO_2 based TC film, as well as the innovative structure of VO_2 based materials. Moreover, properties of TC materials Type 2 and Type 3 were discussed as well.

2.4.1. VO_2 based Thermochromic windows

VO_2 based TC films, as the most promising TC coatings of window glazing, have been significantly developed by various scholars. The scholars and institutions, such as Parkin *et al.* based in University College London (UCL), Gao *et al.* based in China Academy of Science (CAS), and Lawrence Berkeley National Laboratory (LBNL). Parkin *et al.* conducted most of the research in the field.

They mainly studied about chemical vapour deposition of the metal dopant VO_2 film [44, 45], nano-composite TC thin film and their energy efficient application [13], novel VO_2 based coating achieving high visible transmittance [46]. Gao *et al.* studied the solution-based fabrication of VO_2 based TC film, an innovative structure of VO_2 nanoparticles. Additionally, Gao *et al.* [10] measured energy saving performance of TC glazing in buildings through simulation and small-scale experiment. In LBNL, studies were undertaken on the optimum fabrication of VO_2 nanoparticles by physical vapour deposition and simulation of the energy saving potential of TC windows applied in commercial buildings [16, 47].

2.4.1.1. Fabrication methods

Alternating the process of fabrication is one of the effective methods to improve thermochromic properties, i.e., transition temperature, change of visible and NIR transmittance. The experiments conducted by Parkin [48, 49], Gao [50] and Burkhardt [51] proved that it is the microstructure of VO_2 film which significantly affect thermochromic properties. Under different preparation conditions, various microstructures of the VO_2 film were obtained. Previous literature indicated that three approaches had been commonly used to fabricate VO_2 films, and coat them on glass [10]:

Physical vapour deposition (PVD) is mainly achieved by reactive sputtering, which consists of three steps, including evaporation, reactions and deposition. VO_2 thin films were initially grown using reactive sputtering by Fuls, Hensler, and Ross of the Bell Telephone Laboratories [52, 53]. Burkhardt [51, 54], Guinneton [55] and Wang [56] have undertaken the study on depositing VO_2 thin films by PVD methods. Additionally, PVD was used to produce tungsten dopant VO_2 (W-doped VO_2) or other Vanadium compositions [57-60].

The advantages of PVD are easy to produce uniform films and suitable to use on both small and larger scale substrates. Additionally, the deposition is high-efficient [11]. However, since it is an off-line process with slow growth rates, relatively poor adhesion was obtained, and expensive equipment was required [41].

Chemical vapour deposition methods (CVD) is a standard industrial deposition process for producing premium quality and highly functional thin films [61]. CVD for the deposition of VO_2 thin films was firstly reported by Koide and Takei in 1966 and further developed by Chesnut *et al.* [61]. Atmospheric pressure chemical vapour deposition (APCVD) [41, 49, 61-64], and aerosol assisted chemical vapour deposition (AACVD) [44, 61, 65] are the two main methods of CVD. Both of them are commonly applied to deposit VO_2 films on glass and fabricate dopant VO_2 thin films. By controlling the annealing temperature, CVD is effective to produce VO_2 based film with relative lower transition temperature range [44, 48, 49, 63, 64, 66].

The CVD techniques enable highly pure, dense materials and uniform films with excellent adhesion, the deposition rates are high and adjustable. Low temperatures and inexpensive precursors are required [41]. However, it is difficult to deposit multi-component materials [65].

Solution-based methods. The sol-gel method is straightforward to operate, but the time required to obtain the solution is significant for forming the desired products, resulting in a slow multi-step process [61]. For example, the preparation of VO_2 films by sol-gel method begins with a dip- or spin-coated sol-gel Vanadium oxide (V_2O_5) film, and then heat treatment is conducted under a vacuum atmosphere [61]. Recent studies on the sol-gel processing of VO_2 have been focused on the formation of VO_2-based composites and optimisation of their optical properties [10, 50, 67, 68].

The sol-gel method is relatively low cost and suitable for depositing in a large-area surface. By using sol-gel methods, the dopant in the VO_2 film is easy to be achieved, and low processing temperature is required. However, the very large area of glass and multi-layer thin films are difficult to achieve [11, 61].

2.4.1.2. Transition Temperature

The transition temperature (T_t) is one of the significant properties of TC glazing when undergoing TC transition from clear to tinted states under different climatic conditions. T_t of pure VO_2 crystals is 68 ºC [69], and that of un-doped VO_2 films is ranging across 50-66 ºC [49], both of them are too high to be achieved in practice. As aforementioned, CVD fabrication method is effective to change the Tt of VO_2 based film. On the other hand, doping additional metal into VO_2 based film also can reduce Tt. This section summaries the VO_2 based TC films with different ranges of transition temperature:

a) Transition temperature below 20 ºC

Tungsten doping (W-doping) has been proved to be the most effective method to reduce the transition temperature of VO_2. By using the APCVD, tungsten-doped (W-doped) VO_2 was produced and proved to cause a noticeable reduction in transition temperature. Figure 2.7 presents that the transition temperature decreases linearly with increasing atom percent of tungsten doped in VO_2 [41]. It is found that deposition under WCl_6 bubbler temperature of 130 °C, resulting in a VO_2 film with 1.56 at% W-dopant concentration, and a transition temperature of 20 °C (±2.5). While with WCl_6 bubbler temperature of 152 °C, a VO_2 film with 1.75 at % W-dopant concentration, and the transition temperature of 5 °C was obtained [66].

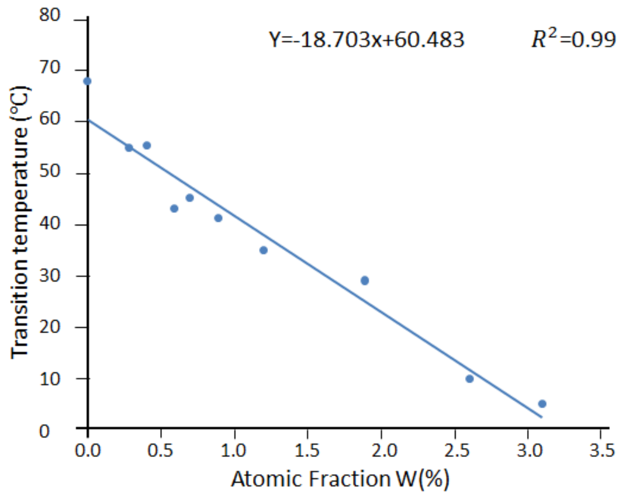


Figure 2.7: Change in transition temperature of the VO_2 film with W atom percent [41]

b) Transition temperature within 20 °C - 30 °C

W-doped (tungsten-) and F-doped (fluorine-)VO_2 were produced by reactive sputtering and studied in the 1990s [70]. It indicated that the transition temperature of W-doped VO_2 film can be reduced by 20K with 1% increase of W-dopant concentration. The F-doped film has a similar trend with W-doped VO_2 film, and co-doped of 1% F and 0.8% W could result in 25 °C Tt of VO_2 film [51]. The sol-gel method was applied to improve the properties of W-doped VO_2 film, and it was found that the transition temperature could be reduced by 15.5 °C with increasing 1mol of W-doping. Thus a VO_2 film doped with 2.7 mol% of W-dopant, results in a Tt of 25 °C [71].

c) Transition temperature within 30 °C - 40 °C

Hybrid AACVD and APCVD methodology have been applied to produce VO_2 thin films. By adding Tetraoctyl ammonium bromide (TOAB) into the aerosol precursor solution, the particle size was halved, resulting in a significant reduction of the transition temperature to 34.8 ºC [72]. The Hybrid CVD method enables a the transition temperature reduction of VO_2 film to 53 ºC, while affected by TOAB, its transition temperature was controlled in the range across 34-43ºC [72].

d) Transition temperature over 40 ºC

Adjusting conditions during fabrication also enable the reduction of Tt. Fabricating W-doped VO_2 using APCVD methods at the annealing temperature of 500-600 ºC could result in a reduced Tt to 42 ºC [63, 64]. Otherwise, combining dioxide (TiO_2) or cerium oxide (CeO_2) nanoparticles with VO_2 improve both photocatalytic and thermochromic characteristics, and Tt is ranging across 50-60 ºC [62, 73, 74]. SiO_2 also has the potential to reduce Tt of VO_2 film to 61 ºC. Depositing platinum (Pt) on VO_2 films could reduce transition temperature by 9.3 ºC to about 58 ºC [75]. Additionally, Binions *et al.* [45] used CVD methods to produce the Gold-doped VO_2 film, whose transition temperature is 50 ºC.

Additional metal doping into VO_2 film would lead to the change of colours at the same time. Figure 2.8 summarised colours (represented by colours of the columns in the figure) and Tt of the most common used VO_2-based material.

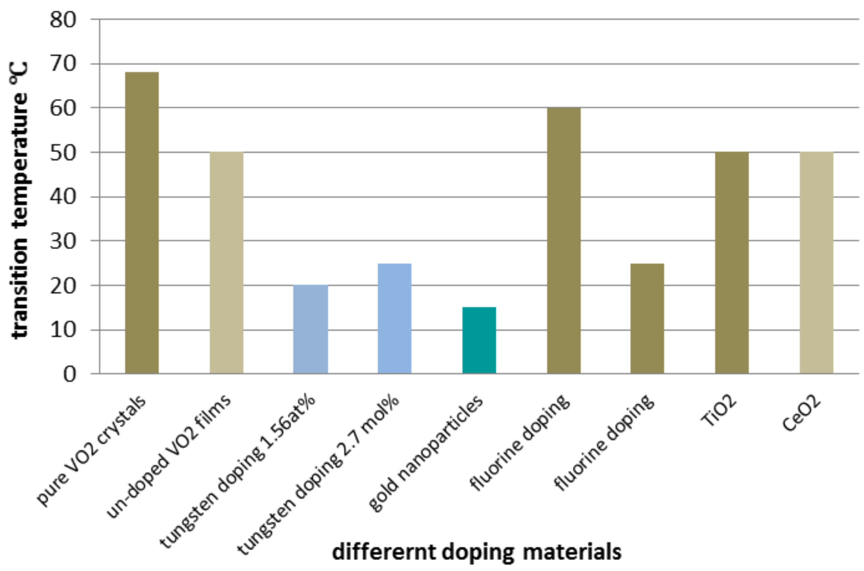


Figure 2.8: Transition temperature variations with different doping materials and predicted colour after transitions (pure VO_2 crystal [64, 69]; Un-doped VO_2 films [49]; W-doping 1.56 at % [66]; W-doping 2.7mol% [71]; Gold nanoparticles [13, 45, 72]; F-doping [54, 76]; TiO_2 [73, 77]; CeO_2[73])

2.4.1.3. Change of visible and NIR transmittance

During the process of reducing transition temperature of VO_2-based materials, optical properties (i.e., transmittance, reflectance, absorptance) during the transition was affected simultaneously. For a pure VO_2 film with a thickness of 50nm, the visible spectral transmittance is up to 40%, and modulation of NIR transmittance is around 30% at 2500nm [78], which is not sufficient to meet the requirement of application in buildings. Therefore, different methods were developed to improve TC optical properties:

- **Fabrication methods**

Fabrication methods used to lower the transition temperature of VO_2-based TC film affect their optical properties as well. For instance, F-doping can increase the visible transmittance of VO_2 film to around 70%, but the transition temperature is ~60℃, which is too high to be used in buildings [76]. On the other hand, adding anti-reflective coatings to W-doping VO_2 films enables the increase of visible transmittance over 60%, and meanwhile, the Tt can be controlled within the desirable range (i.e., room temperature) [54]. Additionally, as is shown in Figure 2.9, reducing the thickness of VO_2 films also increase the visible transmittance, however, the change of NIR transmittance during the transition may be more limited than the thicker one [78].

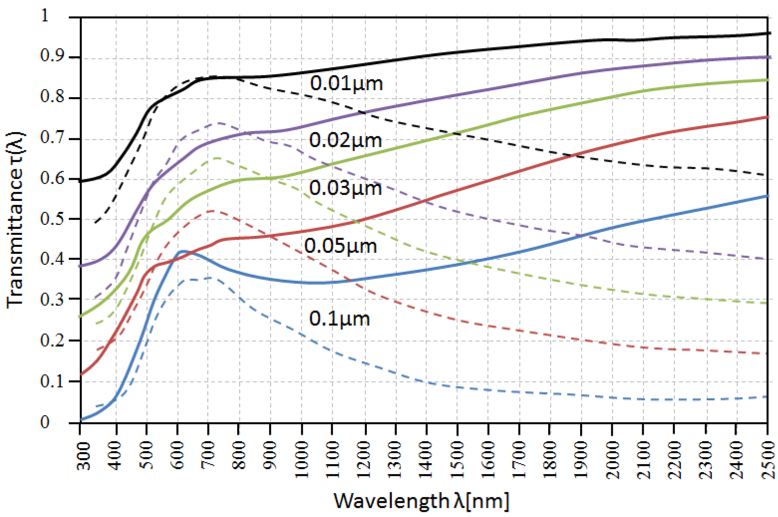


Figure 2.9: Spectral transmittance of VO_2 films with different thickness [78]

Figure 2.10 summarised the optical properties of the different types of VO_2 films produced by various fabrication methods and doping material, as well as with different film thickness. The present optical properties include 1) the peak values (at around 550nm of wavelength) of spectral visual transmittance at the clear state and tinted states; 2) the peak values (at around 2500nm of wavelength) of spectral NIR transmittance at the clear and tinted states, respectively.

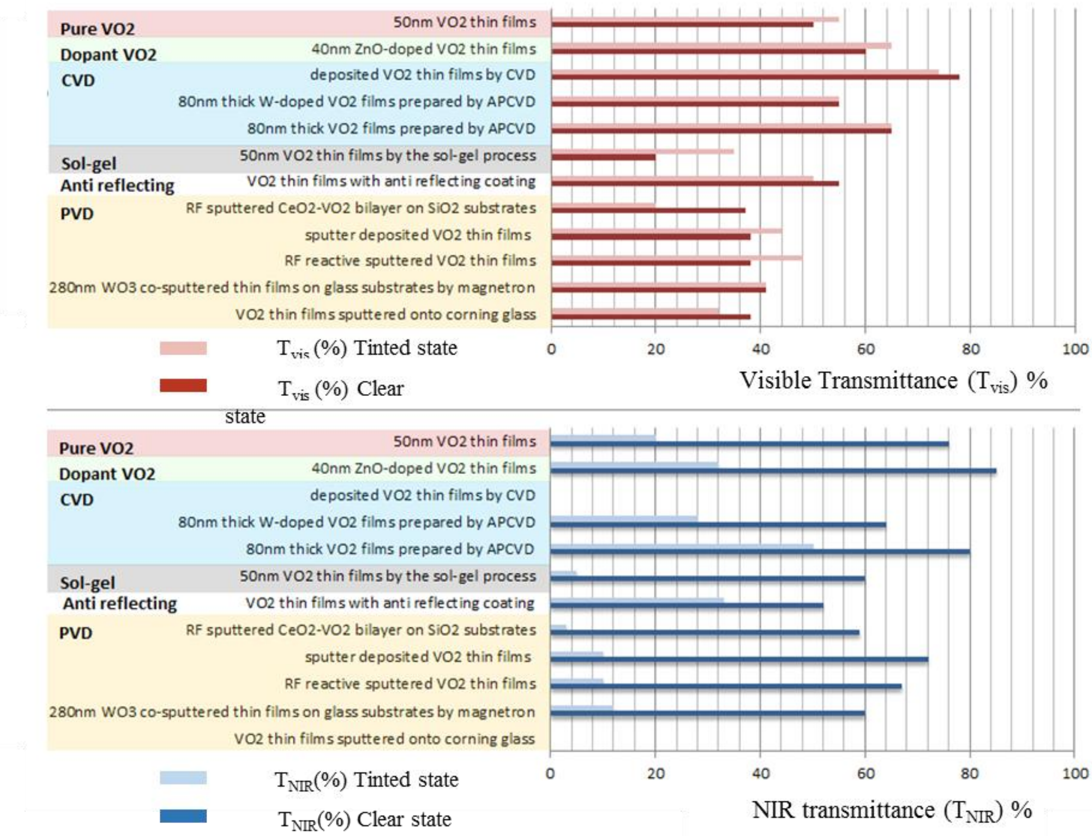


Figure 2.10: transmittance values for various VO_2 coatings before and after transition temperature [58, 66, 74, 79-86]

It can be seen that, in Figure 2.10, the VO_2 based TC films produced by sol-gel and PVD methods all have a low visible transmittance ranging from 20% to 48%. While they have an outstanding modulation of NIR transmittance between clear and tinted states, which is within the range of 56% to 60% at 2500nm. However, the remaining VO_2 based TC films have a relatively high visible transmittance ranging from 50% to 78%, but their capability of changing NIR transmittance is restricted, and the modulation is ranging from 20% to 56% at 2500nm. Noted that it is difficult to achieve both high visible transmittance and large modulation of NIR transmittance.

- **Multi-layered system**

Explorations about VO_2 applications for smart windows have been undertaken, especially in cooperation with other techniques [87-89]. Cooperation with Antimony-doped Tin Oxide (ATO) nanoparticles resulted in VO_2/ATO/polymer thermochromic smart glass foil. It increases the capacity of blocking solar heat gains and leading to lower indoor temperature in hot climates [87]. VO_2/FTO/substrate double-layered films showed excellent low-e performance and thermochromic features [89]. TiO_2/VO_2/FTO substrate structure resulted in an improvement of visible transmittance by 29.4%, and the emissivity is reduced to 0.13 [89]. Additionally, the VO_2/metal multilayer smart window is another new technique to broaden the modulation of thermal emissivity during the TC transition [90].Table 2.1 reports the optical properties of VO_2 based multi-layered smart-window system, and $TiO_2/VO_2/TiO_2/VO_2/TiO_2$ present the largest modulation of spectral average solar transmittance between clear and tinted state, ΔT_{sol} =11.8%.

Table 2.1: Spectral average transmittance metrics for a variety of VO_2 based multilayer smart-window systems [46]

Top…/bottom	**Thickness (nm)**	**Tinted state %**		**Clear state %**		**ΔT_{sol} %**	**Citation**
		T_{sol}	T_{vis}	T_{sol}	T_{vis}		
TiO_2/VO_2	40/50	37.1	45.5	45.0	49.9	7.90	[91]
$TiO_2/VO_2/TiO_2$	25/50/25	40.8	54.9	44.9	57.9	4.10	[92]
ZrO_2/VO_2	56/50	37.9	48.5	43.6	51.3	5.70	[93]
a-Si/VO_2/a-Si	25/100/25	18.0	6.9	26.9	10.0	8.90	[94]
a-$SiO_{0.3}/VO_2$/a-$SiO_{0.3}$	25/100/25	31.4	34.9	35.0	35.6	3.60	[94]
$TiO_2/VO_2/TiO_2/VO_2/TiO_2$	130/40/130/40/130	40.4	43.1	52.1	45.3	11.80	[95]

- **Innovative structures**

From 2010, a new concept nano-thermochromic has been put forward and studied. Li *et al.*, Gao *et al.* and Lawrence Berkeley National Laboratory (LBNL) all carried out studies about the fabrication of VO_2 nanoparticles [8, 47, 87]. Compared with conventional VO_2 film, VO_2 nanoparticles present two main advantages as is shown in Figure 2.11:

1) Dilute suspensions of VO_2 nanoparticles result in little scattering, which could improve visible transmittance in the nanoparticle layer [8]. The increase of spectral

average visible transmittance (T_{vis}) is about 20% when compared with conventional VO_2 film. They both have the same content of VO_2.

2) At the tinted state, optical absorption can be changed to a shorter wavelength in the NIR range to reduce the high solar intensity, and further increase the modulation of solar transmittance (ΔT_{sol}) [8]. The increase of the solar transmittance modulation (ΔT_{sol}) is up to 10%.

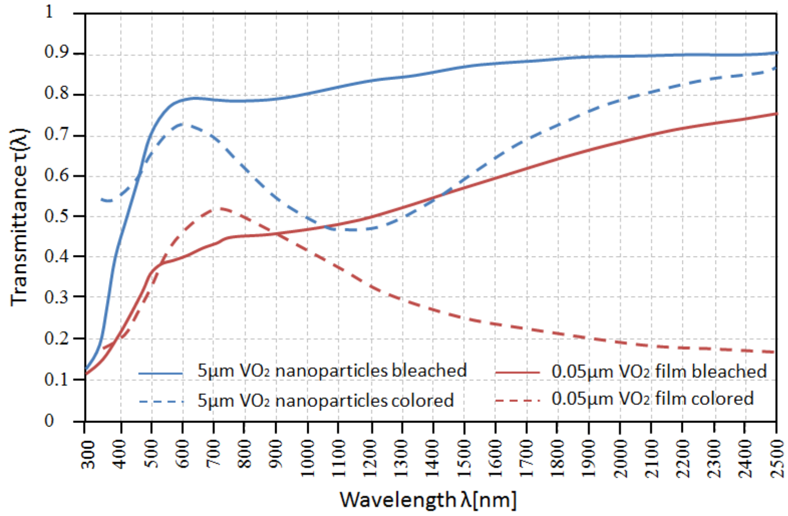


Figure 2.11: Spectral transmittance of VO_2 nanoparticles and film [8]

As is shown in the Figure 2.12 [8]. Nanoparticles have many different geometrical configurations and do not distribute homogenously in their medium. Usually, the nanoparticles are shown as spherical, oriented prolate, oriented oblate and random prolate and oblate. And aspect ratio m is defined as a (major axis) /c (minor axis) for prolate and c/a for oblate. For nanoparticles, the influence factor of optical properties as what is thickness for normal VO_2 films (see figure 2.8) is aspect ratio *m*. Calculation and experiments present that increasing value of *m* (i.e., m= c/a) can lead to higher visible transmittance both in clear and tinted state.

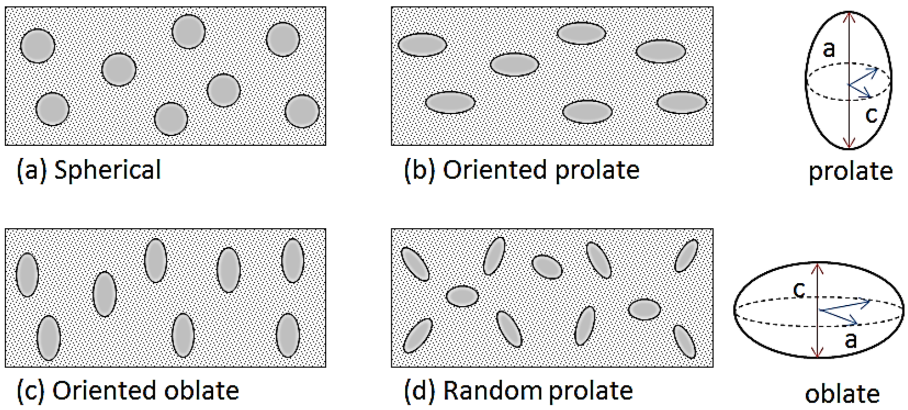


Figure 2.12: Different structures of VO_2 nanoparticles [8]

2.4.2. Complex and polymer TC materials

Wei *et al.* [9, 96] studied an innovative thermochromic material based in Ionic liquid. Figure 2.13 (a) shows the thermochormic properties of composite film of ionic-liquid-nickel-complex-polymer containing $[bmin]_2\ NiCl_4$ [9]. Its colour changed quickly from clear to royal blue, with the temperature increasing from 25 to 75°C. Meanwhile, the increasing absorbance can lead to a decrease of transmittance within wavelength 400-800nm, covering the visible spectrum range.

Figure 2.13 (b) presents the ionic liquid based film containing $[Ni(Me_4en)(acac)]\ ClO_4$, which has the colour tinted from grass green to brown with temperature rising from 25°C to above 70°C. However, their responses in NIR range haven’t been mentioned [9]. Their thermochromic properties within visible spectrum indicated that daylighting levels could be adjusted by this type of TC films applied in windows.

Regarding the thermochromic type 3 mentioned at the beginning of section 2.4, Suntuitive, produced by Pleotint is an extruded polyvinyl butyral (PVB) interlayer [43]. It is a thermochromic interlayer which dynamically changes its capability of admitting solar radiation depending on heat from direct sunlight. Both visible and NIR transmittance decreases at the same time, e.g. Suntuituve glass system named as Starphire has its visible transmittance varying from 55% to 8%, and solar transmittance is changing from 27% to 8%, continuously with a temperature rising from 10 to 60 °C.

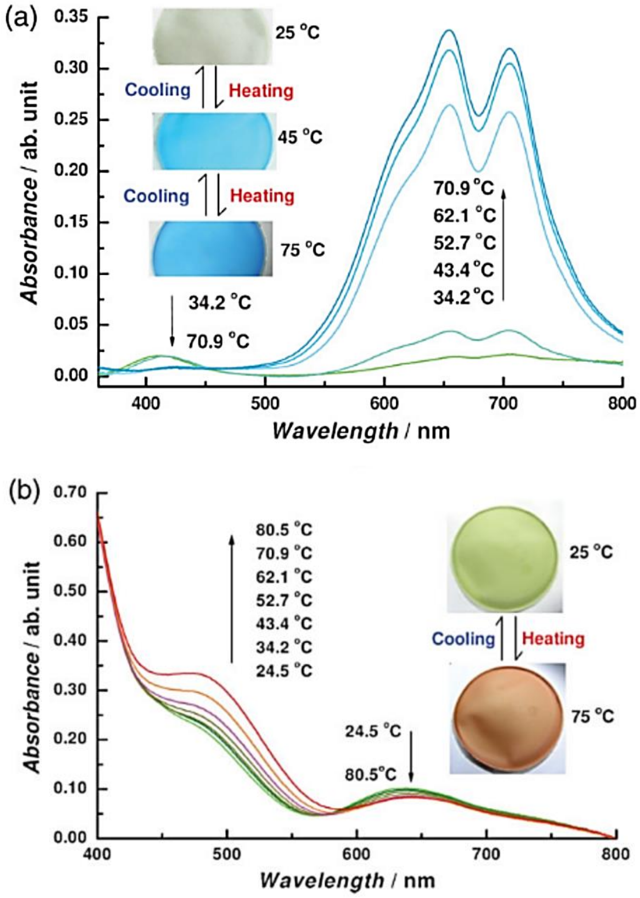


Figure 2.13: Visible spectra and colour photographs of ionic-liquid based thermochromic film
a) is the film of $C_3OHminBF_4$-[bmin]$_2$ $NiCl_4$-PVDF
b) is the film of $C_3OHminBF_4$-[Ni(Me_4en)(acac)]ClO_4-PVDF [9]

2.5. Summary

To sum up, a large number of literature and research indicated that thermochromic windows could passively control solar radiation in spectrum, and have the potential to save energy. Various TC materials were produced by different fabrication methods, aiming to improve thermochromic properties such as the transition temperature, visible transmittance, NIR transmittance. Rarely studies were conducted to evaluate the performance of thermochromic windows applied in buildings, neither considering about their colour properties. Based on current produced thermochromic materials, this thesis conducted a comprehensive investigation through simulation and experiment methods, covering energy and daylight performance, as well as human response to the luminous environment affected by typical TC windows.

Chapter 3

Thermal and Optical Performance of Thermochromic Windows

3.1. Introduction

In order to realize the application of the thermochromic (TC) materials in a building as an energy efficient window component, studies about their energy performance have been conducted. Saeli, Ye, Long, Hoffmann, and Warwick [12, 13, 16, 97] have investigated the building energy saving potential of some TC materials developed in the lab though building energy simulation. When comparing VO_2 based TC windows with low-e and tinted absorbing glass respectively, Saeli *et al*. found that TC windows can reduce more building energy consumption, and this energy saving was more significant in warmer climates rather than in cooler ones [12, 13]. Ye *et al*. [15] investigated the performance of typical VO_2 glazing applied in an office room setting through building energy simulation. It was found that 10.2-19.9% cumulative cooling load could be reduced in comparison to standard clear glazing [15]. In addition, two experiments have been undertaken to test the performance of VO_2-based TC windows. One of the experiments was conducted by Gao *et al.* [10] using a scaled model where the effect of the TC window on the internal space temperature was monitored; it was observed that the studied TC glazing could reduce the indoor temperature by 9°C. The other experiment was carried out by Ye and Long [10, 15, 98] as a full-scale model to validate the building simulation and test the daylight availability. The measurements showed that ~80% illuminance was blocked.

With the purpose of understanding the optical properties (i.e. solar transmittance, absorptance, reflectance, and long-wave emissivity) of TC windows that may affect their energy performance, some hypothetical studies were conducted. Ye *et al.* [99] found that, in comparison with solar transmittance, lower long-wave emissivity can result in more energy saving; and a high absorptivity after transition for TC windows may result in higher energy consumption. Ye and Long [14, 98] developed a series of indexes to estimate whether a TC material could be categorized as energy efficient, such as Energy Consumption Index (ECI), Energy Saving Equivalent (ESE), Energy Saving Index (ESI) and Smart Index (SI). Their studies further indicated that a VO_2 material, which has a large decrease of solar transmittance and a lower increase of absorptivity after the transition, has larger energy saving potential [14, 98]. Warwick *et al.* [97] studied the relationship between transition temperature and theoretical hysteresis gradients and found that TC glazing with the lowest transition temperature and sharpest hysteresis gradient could reduce 51% of the energy demand in comparison to standard clear glazing. Moreover, the hysteresis gradient was significant in enhancing energy saving [97]. Hoffmann studied a series of hypothetical TC windows with different transition temperatures to find the optimised thermochromic characteristics. This study quantified window solar heat gains, heating, cooling, and lighting energy use, all which would be influenced by these hypothetical TC windows. The effect of different window sizes and orientations under various climatic conditions on both energy consumption and visual comfort were studied. It was found that the TC windows reduced the number of hours that occupant glare and discomfort occurred whilst 13.7%-16.7% energy consumption could be reduced with optimised orientation and large-area windows in hot climates [16].

A large proportion of previous studies focus on material development of VO_2-based TC windows [10, 61, 100], whilst only a limited number of simulations have been carried out to understand their effects on the energy performance and visual comfort of a building whilst also incorporating the lab development of TC materials [12, 13, 15, 98]. This chapter aims to explore the thermal and visual performance influenced by current lab-developed TC materials working under different climatic conditions in China. It also, therefore, explores TC performance in an increased level of detail relating to the following research questions:

1) Which climatic zones are most suitable for VO_2 based TC windows?

2) Will TC materials with lower transition temperature close to room temperature (20-25°C) result in larger energy reduction than those with a higher transition temperature?

3) Will TC materials with a large increase in absorptance after transition be more energy efficient?

4) Will TC materials reduce illuminance levels within indoor spaces, while simultaneously decreasing the risk of glare in comparison with traditional clear glazing?

5) What is the best lab developed TC window for various climatic zones throughout China?

3.2. Methodology

This study was carried out by modelling a typical office installed with different types of windows and investigating their performance under five different climates in China. EnergyPlus was used to conduct a series of computation, aiming to obtain significant values including tinted hours, solar heat gains coefficient (SHGC), energy consumption, Useful daylighting illuminance (UDI), etc.

3.2.1. Climates

This simulation was calculated by averaging one hour time steps for a year using the IWEC (International Weather for Energy Calculation) weather file (The files are derived from up to 18 years (1982-1999 for most stations) of DATSAV3 hourly weather data originally archived at the U. S.) for five different climates in China representative of the following five major climatic zones [101]: Harbin as a severe cold zone (SCZ), Beijing as a cold zone (CZ), Hangzhou as a hot summer and cold winter zone (HSCWZ), Kunming as a temperate zone (TZ), and Guangzhou as a hot summer and warm winter zone (HSWWZ). Detailed location and climatic properties for the zones, such as temperature and solar radiation, are specified in Table 3.1 [102]. The average monthly temperature for each zone is shown in Figure 3.1, where it can be seen that Harbin has the lowest average winter temperature of -20°C in January and a relatively warm summer of 22°C, where space heating is dominated. Guangzhou has a monthly average temperature ranging from 15-30 °C throughout the year, where cooling is primarily required. For Beijing and Hangzhou, both heating and cooling are required, however, due to the fact that Kunming has a temperate climate, there are times when neither heating nor cooling is required. In terms of incident solar radiation, summer months have a higher average than that of winter months. Additionally, it is necessary to notice that with decreasing latitude of the cities, solar altitude (i.e. the angle of the sun relative to the Earth's horizon) increases correspondingly, which might affect the daylighting accessibility into the building via the windows.

Table 3.1: Climatic properties of five representative cities in different climatic zones in China [102]

	Location		**Temperature (°C)**		**Solar radiation (W/m^2)**		**Climatic zones**
	latitude	longitude	Max.	Min.	Max.	Min.	
Harbin	45.7°N	126.7°E	29	-28.4	186.8	112.4	SCZ
Beijing	39.8°N	116.5°E	37.1	-10.1	156.4	93.2	CZ
Hangzhou	30.2°N	120.2°E	35.6	-1.8	114.3	61.3	HSCWZ
Kunming	25.0°N	102.7°E	27.4	-1.3	160.5	55.0	TZ
Guangzhou	23.1°N	113.3°E	35	6.6	142.4	38.6	HSWWZ

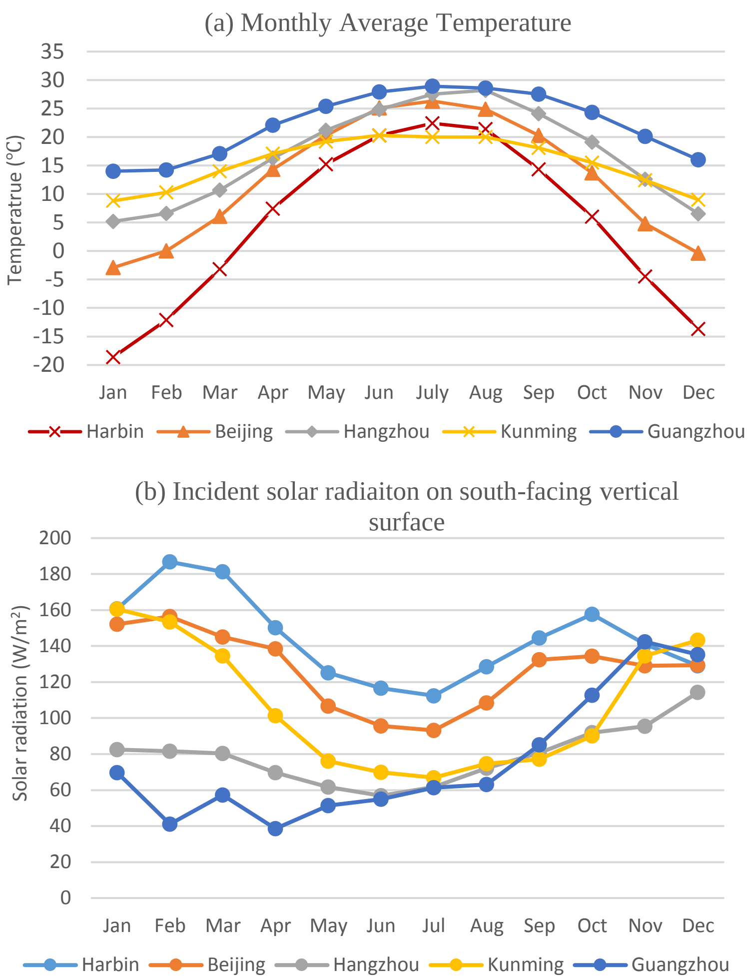


Figure 3.1: Monthly average temperatures (a) and solar radiation incident on the vertical surface of the south wall (b) in five selected cities respectively [102]

3.2.2. Simulation set up

3.2.2.1. Model setting up

The energyplus software was developed by Lawrence Berkeley National Laboratory (LBNL) and the US Department of Energy, which has been widely used to simulate and evaluate the performance of buildings [103]. It has also been used for studies of TC windows and other advanced glazing systems [12, 16, 97], and has been proven to be one of a highly appropriate building simulation program in the field. It was, therefore, chosen to study the thermal and daylight performance of the selected TC windows.

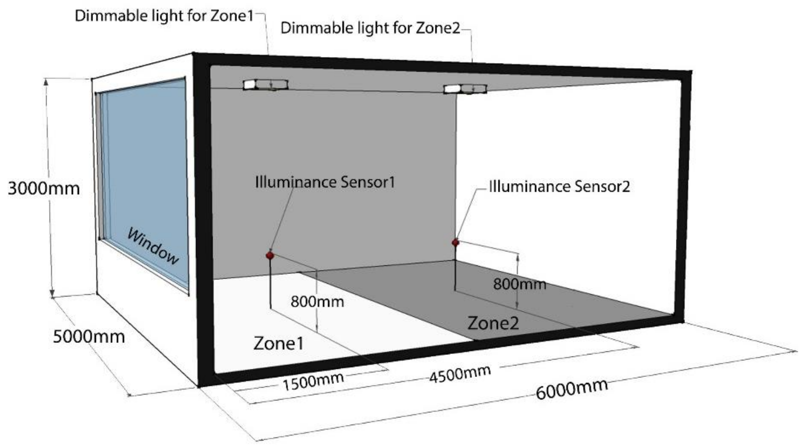


Figure 3.2: A typical office room with a 4.5m×2m window (located over 60% of the wall)

A typical office room with external dimensions of 6m×5m×3m (length × width × height) was constructed in EnergyPlus for this study. The room was modelled to be a mid-floor office within a multi-story building, representative of a generic south facing office in the northern hemisphere. Adjacent offices on the same floor were assumed to be conditioned uniformly, and both the floors above and below were buffered by free running rooms (room without thermal control by HVAC). According to the energy efficiency building standards in China [104], thermal properties of building envelopes have different requirements under different climate zones. It is difficult to reflect this climate consideration within a single model. Therefore, the options decided which satisfy the thermal requirements as much as possible. For the settings of the building envelopes, the U-value of the external wall was set to be 0.43W/m^{2}k, the ceiling 1.21 W/m^{2}k and the floor 1.13 W/m^{2}k. Five types of TC windows, as well as the reference clear window, were all based on double-glazed systems (U-value 2.7W/m^{2}k), and without shading devices installed.

As Figure 3.2 illustrates, the artificial lightings were controlled by a two-zoned automatic dimmer for supplying the natural daylighting, to meet the illuminance target level of 500lux at working plane in an office, with a distance of 800mm from the floor

[105]. The two illuminance sensors were designated in the centres of two zones respectively to monitor the horizontal daylight illuminance and control dimming: Sensor 1 is in zone 1 close to the window (1.5 meters away), and Sensor 2 is in zone 2 further away from the window (4.5 meters away). Internal loads and schedules were set up as: An occupant density is 18.6m^2/per person, and primarily occupied the room between 9 am to 5 pm on weekdays. Equipment loads were 13W/m^2, and lighting loads were 11W/m^2. In order to diminish the influence of HVAC systems and highlight the building performance affected by different types of TC windows, indoor temperature was controlled to a constant 21ºC, appropriate for both winter and summer in the most non-domestic building applications [106]. In order to quantify the performance of TC windows influenced by window size, the Window-to-Wall Ratio (WWR, defined as net glazing area/ total wall area where window is located) was set from 0.1 to 1 with intervals of 0.1, i.e. first simulation model has WWR of 0.1, and second one has WWR of 0.2, and so on.

3.2.2.2. Materials

Five types of TC glazing were selected, and Table 3.2 shows properties of an external layer of double glazing: WV_t20 is a W-doped VO_2 film with the characteristic of lower transition temperature of approximately 20ºC [66]. WV_t40 is VO_2 film fabricated by co-sputtering coated with W-doped with a transition temperature of 40ºC [86]. VO_2_t38 is glazing with VO_2 film fabricated by hybrid aerosol assisted and atmospheric pressure chemical vapour deposition (AA/AP CVD) with the reaction of vanadyl acetylacetonate and TOAB, with a transition temperature of 38.5ºC [12]. VO_2_t41is another pure VO_2 film manufactured by State Key Laboratory of High-Performance Ceramics and Superfine Microstructure, Shanghai Institute of Ceramics (SIC), Chinese Academy of Sciences (CAS) with a transition temperature of 41.3 ºC [15].

NVO_2_t40 is a VO_2 nanoparticle coated glazing, a novel VO_2-based material with a hypothetical transition temperature of 40ºC [8]. According to their characteristics, the five types of TC glazing were categorized into three different groups:

1) The high visual transmittance of approximately 0.6 at cold state (VO_2_t38 and NVO_2_t40).
2) Similar average solar and visual transmittance of approximately 0.45, but different transition temperature varying from 20°C to 40°C(WV_t20, WV_t40, and TC_VO_2).
3) Same transition temperature (40°C) and a similar reduction of solar transmittance after the transition of approximately 12% (WV_t40and NVO_2_t40).

Table 3.2: Properties of selected VO_2-based TC glazing

Properties	WV_t20		WV_t40		VO_2_t38	
	S-state	**M-state**	**S-state**	**M-state**	**S-state**	**M-state**
Transition temperature (T_t)	20ºC		40ºC		38.5ºC	
Colour	Green/Blue		Green/Blue		Yellow/Brown	
Solar transmittance (T_{sol})	0.44	0.39	0.412	0.288	0.460	0.380
Visible transmittance (T_{vis})	0.39	0.39	0.394	0.346	0.610	0.510
Solar reflectance (ρ)	0.18	0.20	0.067	0.082	0.230	0.210
Solar absorptance (α)	0.38	0.42	0.521	0.630	0.310	0.410
Long wave emissivity (e)	0.84	0.84	0.840	0.840	0.830	0.790
Properties	**VO_2_t41**		**NVO_2_t40**		**Clear Glazing**	
	S-state	**M-state**	**S-state**	**M-state**	**---**	**---**
Transition temperature (T_t)	41.3ºC		40ºC		---	
Colour	Yellow/Brown		Yellow/Brown		Nature	
Solar transmittance (T_{sol})	0.440	0.355	0.69	0.57	0.78	
Visible transmittance (T_{vis})	0.435	0.421	0.63	0.60	0.88	
Solar reflectance (ρ)	0.078	0.055	0.05	0.06	0.08	
Solar absorptance (α)	0.482	0.590	0.26	0.37	0.14	
Long wave emissivity (e)	0.880	0.880	0.84	0.84	0.84	

***S-state is the semiconductor state at a lower temperature than transition temperature, also named 'clear-state.'**
***M-state is the metallic state at a higher temperature than transition temperature, also named 'tinted-state.'**

To facilitate analysis and comparison, some assumptions were made: 1) Based on the report of the performance of these selected TC glazing the transition temperature range was assumed to be 8°C uniformly for each material, and there is no thermal hysteresis during the process of temperature increasing and decreasing [97]. 2) TC material used in glazing NVO_2_t40 was assumed to have a transition temperature of 40°C. Because the real transition temperature is around 60°C, which is too high to achieve thermochromic transition practically under most of the climatic conditions, and 40°C is a transition temperature potential to be achieved in terms of TC materials fabrication [12, 15]. 3) Some missing data such as long wave emissivity was assumed to be the same as that of clear glazing (0.840), based on existing data ranging from 0.79 to 0.88 [12, 14-16, 98].

3.2.3. Principles of TC windows in EnergyPlus

As aforementioned, indoor temperature during working hours was set up as constant 21°C, so the crucial elements influence TC layer temperature is outside temperature and incident solar radiation on window surface. In EnergyPlus, heat balance equations related to both surfaces of outside layer TC glazing is shown as below, the equations indicate that solar absorptance $A_j^{f,dif}$ and $A_j^{b,dif}$ of TC glazing is significant to determine the temperature of windows.

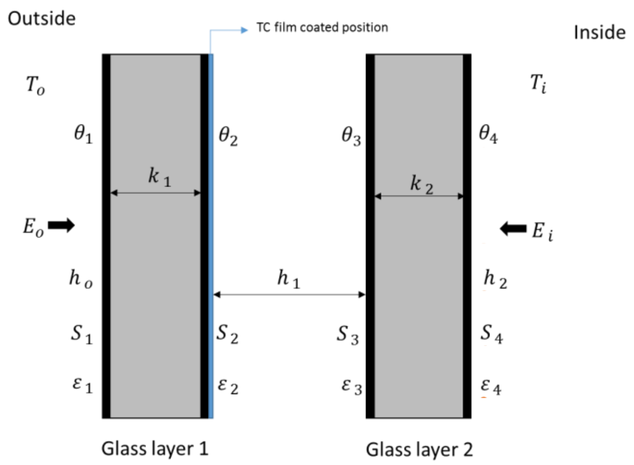


Figure 3.3: Double glazing system showing variables used in heat balance equations

$$E_0\varepsilon_1 - \varepsilon_1\sigma\theta_1^4 + k_1(\theta_2 - \theta_1) + h_0(T_0 - \theta_1) + S_1 = 0 \qquad \text{Equation [3.1]}$$

$$S_1 = S_2 = \frac{1}{2}\left(I_{bm}^{ext} cos\varphi A_1^f(\emptyset) + I_{dif}^{ext} A_1^{f,dif} + I_{sw}^{int} A_1^{b,dif}\right) \qquad \text{Equation [3.2]}$$

Where, σ is stefan-Boltzmann constant, ε_i is emissivity of face i, i=1, k_i is conductance of glass layer i, W/m^{2}K, i=1, h_o is outside, inside air film convective conductance, W/m^{2}K , T_o is outdoor air temperatures, K, E_o is exterior, interior long-wave radiation incident on window W/m^2, θ_i is temperature of face i, K, i=1, 2, S_i is radiation (short-wave, and long-wave from zone internal sources) absorbed by face i, i=1, 2, W/m^2, I_{bm}^{ext} is exterior beam normal solar irradiance W/m^2, I_{dif}^{ext} is exterior diffuse solar irradiance on glazing W/m^2, I_{sw}^{int} is interior short-wave radiation (from lights and from reflected diffuse solar) incident on glazing from inside W/m^2 , I_{lw}^{int} is long-wave radiation from lights and equipment incident on glazing from inside W/m^2 , φ is angle of incidence, A_j^f is front beam solar absorptivity of glass layer j, j=1, 2, $A_j^{f,dif}$, $A_j^{b,dif}$ is front and back diffuse solar absorptivity of glass layer j, j=1, 2

In EnergyPlus, a thermochromic window is described by a Construction object that refer to a special layer, and that layer is defined with the following objects:

1) Window Material: Glazing Group: Thermochromic

2) Window Material: Glazing

An object 1) is defined with a series of object 2) corresponding to each specification temperature. Each specification temperature of the TC coated glazing is calculated by equation 3.1 and 3.2. During the running of EnergyPlus simulation, a series of TC windows is created once corresponding to each specification temperature. The TC windows used for the current time step calculation is based on the most closed temperature of the TC glazing from the previous time step.

3.2.4. Validation of the models

EnergyPlus itself has been developed via experimental analyses, tested according to ASHRAE Standard 140 methodology, with well measured data using relevant test facilities [107]. In this study, a building model similar to previous research by Ye *et al* [15] has been developed in EnergyPlus with same boundary conditions applied. The measured cooling load from [15] and the simulated results from EnergyPlus are illustrated in Figure 3.4. It can be seen that there is no significant difference ($< \pm 5\%$) between the measured cooling load and the simulated results. This provides the confidence for the developed method. Therefore, this method can be further applied to explore the proposed smart window for building application.

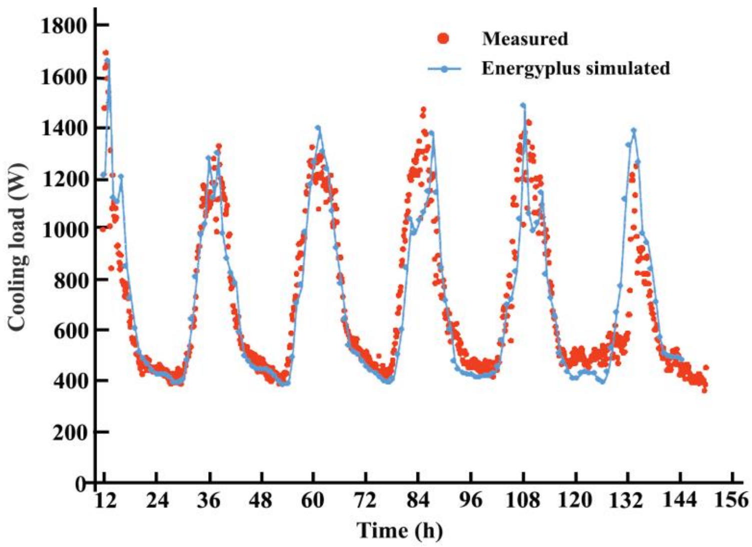


Figure 3.4: Cooling load comparison between EnergyPlus model and experimental measurement

3.2.5. Evaluation criteria

In order to understand the performance of thermochromic windows, specific evaluation criteria were applied for their analysis, including tinted hours, solar heat gain/ loss, SHGC, heating/cooling load, UDI. These particular criteria are explained as follows:

Tinted hours: the number of hours when partially and fully tinted states occur for TC windows [12, 16]. According to the TC layer temperatures, three states were defined: Clear, partially tinted, and fully tinted. As aforementioned, the transition is a gradual process, and the transition temperature range is 8^{o}C for each material, which means that transition is continuous within 8^{o}C around its transition temperature. For example, in terms of a TC glazing with a transition temperature of 40^{o}C, transition occurs with the temperature rising above 36^{o}C. When TC layer temperatures are between 36–44^{o}C, the state is categorised as partially tinted; when the temperature is over 44^{o}C, the state is categorised as fully tinted.

SHGC: The solar heat gain coefficient (SHGC) is the fraction of incident solar radiation admitted through a window, i.e. the ratio of window heat gains to incident solar radiation on the window surface. Window heat gains are made up of two main parts: 1) Solar radiation directly transmitted through the window; 2) Solar radiation absorbed and subsequently released inwards, known as secondary heat gains and expressed as a number between 0 and 1;The lower a window's SHGC, the less solar heat is transmitted into the room.

UDI: Useful Daylight Illuminance (UDI), is the fraction of time when indoor horizontal daylight illuminance at a given point falls into one of the given illuminance ranges (bins), which were defined by splitting the analysed period into a lower and upper illuminance limit. According to published findings [108] on occupant preferences and behaviors, the rationale for the UDI range limits is summarized as the following three: 1) UDI within illuminance range lower than 500lux ($UDI_{<500lux}$) is insufficient to be the sole source of illumination or contribute to artificial lighting significantly, or effective as the sole source of illumination, artificial lighting is required. 2) UDI within illuminance ranging across 500-2000lux ($UDI_{500\text{-}2000lux}$) is desirable or at least tolerable, no artificial lighting is required. 3) UDI falling into illuminance range higher than 2000lux ($UDI_{>2000lux}$) is likely to produce visual or thermal discomfort and shading may be required.

WWR for energy saving (ES) and balanced illuminance (BI): These evaluation criteria are used to analyse how window sizes influence energy saving and illuminance levels. In terms of ES, it is the range of window-to-wall ratio (WWR) when TC windows can provide energy saving compared with the reference (DG) applied in the studied office room. When WWR falls in the range of ES, TC windows applied can be energy saving. Otherwise, they are more energy-consuming than the reference clear double glazing.

BI is the value of WWR when the desired daylight hour of sensor 1 and sensor 2 within the $UDI_{500-200lux}$ bin equate to one another. It is a balance point to get overall improved daylighting distribution in the office.

3.3. Results and Discussion

Energy consumption (i.e. heating, cooling and artificial lighting consumption) and daylight performance (i.e. UDI) of a typical office room with TC windows applied were investigated under five different climatic conditions. In addition, the effect of transition temperatures and optical properties of the VO_2-based thermochromic materials on the performance of TC windows, such as tinted hours, solar heat gains and SHGC have also been investigated. From the perspective of building design, the window size is another crucial element that affects both energy and daylight performance. The criterion for identifying the optimised TC window size was based on achieving a balance between daylight availability and energy-saving potential.

3.3.1. The characterisations of the selected thermochromic glazing

The temperature of the thermochromic glazing correlates with the optical and thermal properties of the thermochromic glazing (e.g. absorptance, solar transmittance modulation, reflectance, and transition temperature) as well as ambient conditions (e.g. outdoor and indoor ambient temperature and incident solar radiation intensity). Therefore, the combination of these effects on window optical and thermal behaviours was investigated, and their impact on the window heat gain and SHGC are also discussed. In addition, the characterisation of selected glazing was investigated under the climatic condition in Beijing. As it has a hot summer and cold winter, Beijing is suitable to be a representative climatic condition to observe the various environmental impacts on the selected types of TC glazing.

3.3.1.1. TC layer temperatures

1) Tinted hours affected by material properties

The state of the TC window (clear or tinted) determines the amount of solar irradiance entering the room. If a thermochromic window is in a partially or fully tinted the state, it results in less transmittance through the window, therefore less solar irradiance entering the room, useful in reducing summer cooling load. Figure 3.5 shows the partially tinted and fully tinted hours of five different types of TC glazing under Beijing's climate. Cooling period is from May to October and heating period ranges from November to April under the assumed HVAC operation condition that the thermostat temperature is fixed at 21 °C during occupied hours throughout the year (excluding weekends and public holidays), as is mentioned in methodology. The number of annual accumulated working hours is 2024. The number of tinted hours for WV_t20 is significantly higher than the other four types of TC glazing, which is 80.0% of the occupied hours throughout the year (Figure 3.5). This is mainly due to the transition temperature of 20°C for WV_t20, which is significantly lower than other types and relatively easy to be achieved under most of the climatic conditions. However, more tinted hours do not reflect higher energy efficiency or better daylight distribution. This is because an ideal thermochromic window is expected to spend most hours during the cooling demand period at its tinted state, in order to block extra solar heat gains transmitted into the room during the cooling season. However, they are expected to admit more solar heat gains for passive heating during the heating season. For WV_t20, 38.6% of the tinted hours occur during the heating period, which may lead to more heating energy consumption to supplement the passive heating. WV_t40, VO_2_t38, VO_2_t41and NVO_2_t40 have annual tinted hours of 39.4%, 20.6%, 29.8%, and 16.4% respectively. Although the annual total tinted hours of VO_2_t38 and NVO_2_t40 are less than the others, their tinted hours mainly occurred in the cooling period, i.e. 88.5% for VO_2_t38, and 89.7% for NVO_2_t40. The distribution of tinted hours is mostly approaching the ideal thermochromic windows, which has tinted state dominant in hot days, and clear states dominant in cold days.

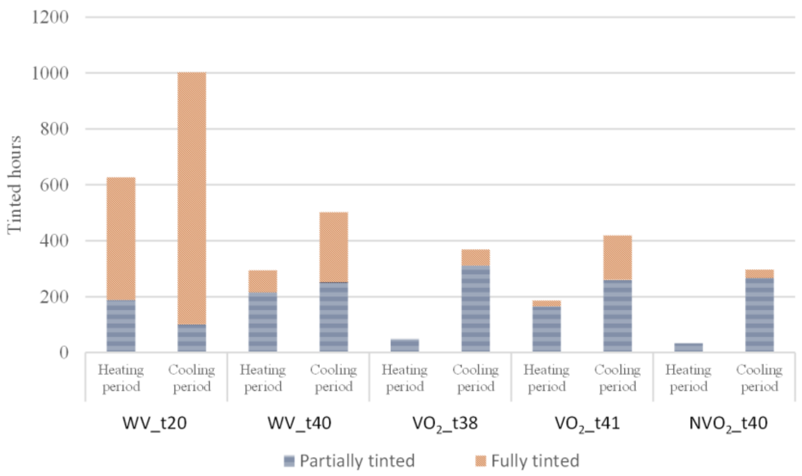


Figure 3.5: Accumulated fully tinted and partially tinted hours of heating/cooling period respectively in Beijing

Tinted hours are affected by transition temperature, solar absorptance, incident solar radiation intensities, ambient temperature and some convection effects. A higher solar absorptance improves the capability of the TC glazing to absorb solar irradiance, therefore increasing the window temperature. This may increase the probability of TC glazing to reach its transition temperature, whereby more tinted hours could be attained. On the other hand, a lower solar absorptance would inhibit the increase of window temperature, thus resulting in fewer occurrences of tinted hours. Figure 3.6 presents the tinted state of all studied TC types affected by their transition temperature and solar absorptance in cooling season. As can be seen, WV_t40, VO_2_t38, VO_2_t41, and NVO_2_t40 have similar transition temperatures ranging from 38.5 to 41.3°C. However, WV_t40 and VO_2_t41 have higher absorptance (i.e. 0.52-0.63 for WV_t40, 0.48-0.59 for NVO_2_t40), thus more tinted hours can be achieved than with VO_2_t38 and NVO_2_t40.

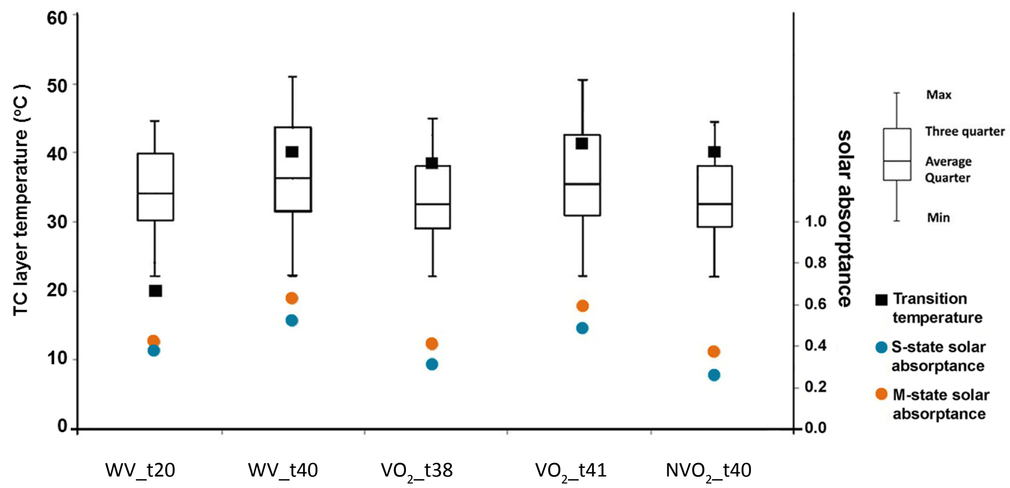


Figure 3.6: TC layer temperature of five TC glazing Beijing during July working hours 9 am to 5 pm with a 21ºC internal temperature controlled by HVAC.

b) Tinted hours affected by ambient conditions

Based on the properties of different thermochromic materials, the studied TC windows can give a different response to the ambient conditions where they are applied. This means that ambient conditions also influence the performance of thermochromic behaviours. With a constant indoor temperature of 21°C, Figure 3.7 illustrates the hourly outdoor temperature and incident solar radiation output for the annual working hours when TC glazing is partially or fully tinted. Each point represents an outdoor temperature and corresponding incident solar radiation value. Consistent with tendency illustrated in Figure 3.5, WV_t20 has the highest tinted hours amongst the five types of TC glazing and most of the hours the glazing is in a fully tinted state. Most cases of tinting occur when the outdoor temperature is above the lower limit of the transition temperature range (i.e. 16°C). However, there are occurrences of TC changing to tinted states when the outdoor temperatures are well below the transition temperature range, due to high levels of incident solar radiation. As can be seen, when the outdoor temperature ranges from 0-10°C, there are tinted hours which occur with incident solar radiation levels between 400 and 900W/m^2. It is indicated that the WV_t20 could also have a thermochromic transition on cold, sunny winter days with WV_t40and VO_2_t41 following similar tendencies. The TC transition occurs when the incident solar radiation levels range from 200 to 900 W/m^2, while the outdoor temperature is between 0-35°C. VO_2_t38 and NVO_2_t40 are another similar groups with relatively low tinted hours and rare full tinted coverage. The main incident solar radiation and outdoor temperature for transition occurrences are 200-800 W/m^2 and 15-35 °C. Since the four types of TC glazing all have relatively high transition temperatures (around 40°C), and the outdoor temperatures of Beijing are predominantly below the transition temperatures, TC transition only occurs when the incident solar radiation levels are sufficient enough to raise the glazing temperature above the transition temperature. As was shown in section 3.1.1.1, a lower solar absorptance of TC glazing restricts the increase of their temperatures. Thus VO_2_t38 and NVO_2_t40 with absorptance ranging across 0.31-0.41 and 0.26-0.37 respectively, are more appropriate for applying under a warmer climatic condition with higher solar radiation.

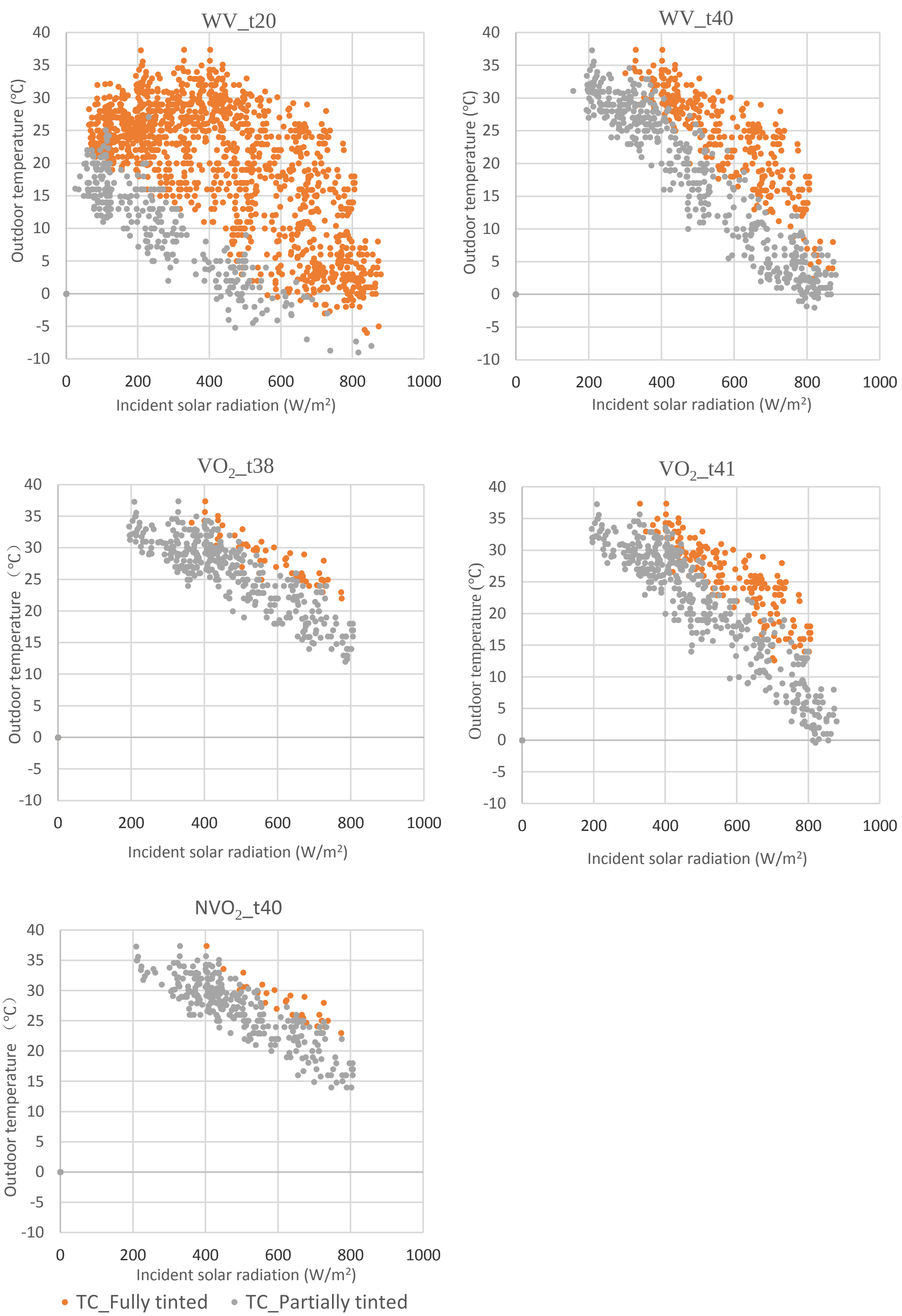


Figure 3.7: The effects of outdoor incident solar radiation and outdoor ambient temperature on TC window state under Beijing's climate the red dots show the hours when the window is fully tinted and grey dots show the hours when the window was partially tinted out of a total of 2024 working hours

3.3.1.2. Window heat gains

Figure 3.9 shows the hourly window heat gain and incident solar radiation of a standard double glazing and TC windows during occupancy hours throughout the year, also under the climatic conditions of Beijing. Each point represents solar heat gain by the window and its corresponding incident solar radiation. Blue points depict standard double glazing, and red points depict TC windows. The SHGC of each TC glazing is illustrated as the slope (k), which is obtained by dividing the value of window heat gain (y-axis) over the incident solar radiation (x-axis).

In the perspective of graphical analysis, the blue points' (DG) distribution is more concentrated than that of the red ones (TC). Therefore, the SHGC of the DG can be represented by a single slope using linear regression. The SHGC of TC windows was defined by two slopes, which present the minimum and maximum values of SHGC respectively.

As can be seen in Figure 3.9, normal double glazing has a constant SHGC of 0.65, which is higher than all studied TC windows. WV_t40 represents the largest variation of SHGC, where the slope change is 0.134, ranging from 0.467 (K1) to 0.333 (K2) and VO_2_t41 has a slope variation of 0.108. Both WV_t40 and VO_2_t41 have relatively large variations of SHGC during the year, which means that they are potentially able to have increased thermochromic performance. Figure 3.8 shows the slopes changing with different states of TC windows in details. Taking WV_t40 working in the hottest month of Beijing as an example, it is noted that the slope is declining from 0.433 to 0.383 with the sequence of clear, partially tinted, and fully tinted window results. The results in a decrease of transferring incident solar radiation to window heat gains. Additionally, fully tinted hours are concentrated in the region with high incident solar radiation (i.e. >120 W/m^2) and the corresponding lower SHGC could reduce cooling requirements.

WV_t20 shows a modest change of SHGC ranging from 0.483 to 0.375, due to its restricted 5% solar transmittance change from 0.44 to 0.39. VO_2_t38 and NVO_2_t40 have relatively large solar transmittance changes, i.e. 8% and 12% respectively, however, they did not show the expected variation of SHGCs, the consequence of their lower tinted hours, as aforementioned.

Moreover, NVO_2_t40 has an SHGC close to traditional double glazing, which varies from 0.625 to 0.516. This indicates that NVO_2_t40 transfers the largest proportion of solar radiation to window heat gains amongst all the studied TC windows. Overall, the TCs follow a similar trend of SHGC variation, with minute differences which correspond to the change of solar transmittance of each TC glazing shown in Table 3.1.

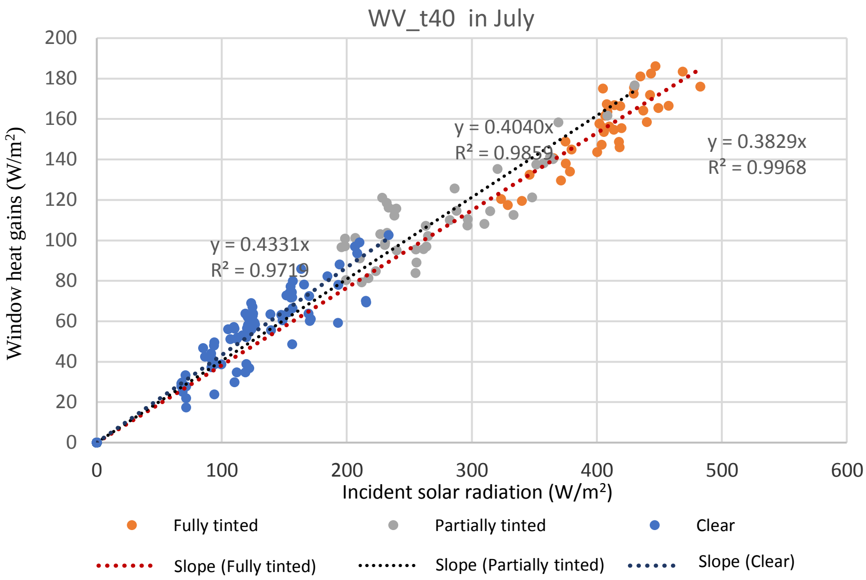


Figure 3.8: The detailed SHGC changing with three states: clear (blue), partially tinted (grey), and fully tinted (red) of WV_t40 in the hottest month of July in Beijing

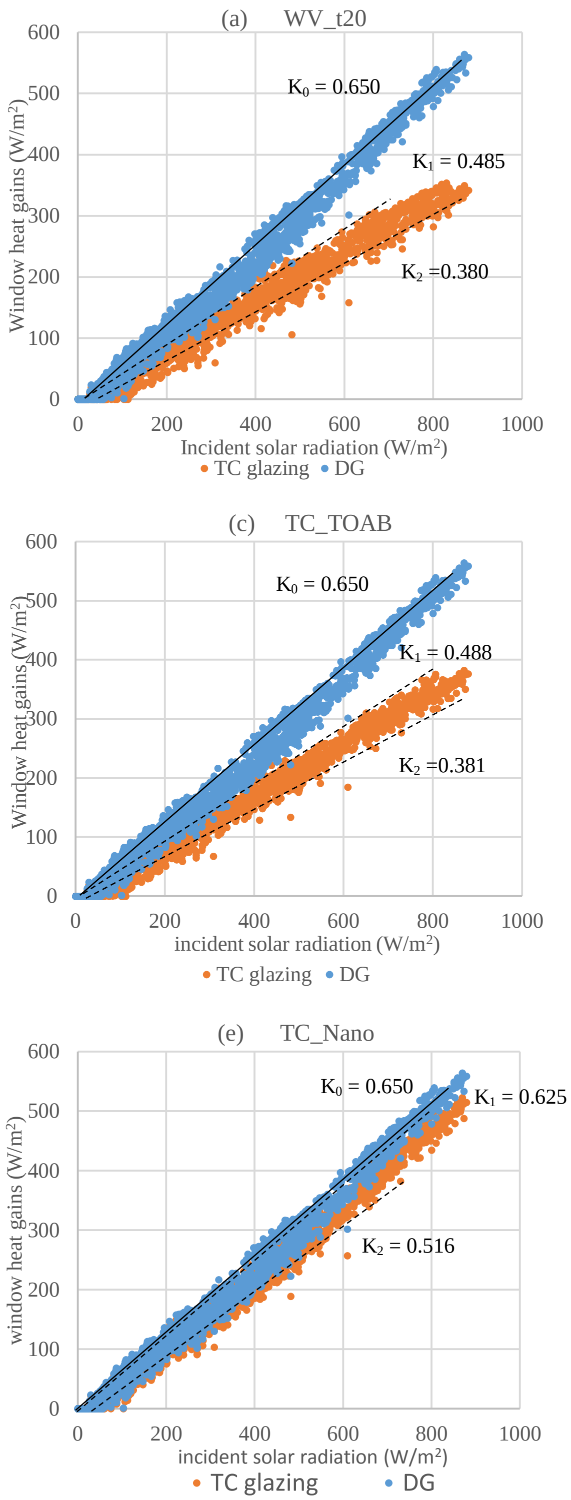


Figure 3.9: Solar Heat Gain Coefficient (SHGC) of standard double glazing and five studied TC windows annually in Beijing

The values of SHGC only show the capability of TC windows for transferring incident solar radiation to window heat gains annually. However, window heat gain can be either beneficial or detrimental to the heat balance and energy consumption of the building. The ideal thermochromic window would limit solar heat gains when the thermal zone is in cooling mode and admit solar heat gains when the zone is in heating mode.

Figure 3.10 shows the window heat gains caused by all studied TC windows and reference double glazing during the heating period (Nov to Apr) and cooling period (May to Oct) respectively under the climatic conditions of Beijing. As can be seen, total window heat gains of all windows during the heating period are higher than that of the cooling period, caused by a larger transmitted solar radiation during winter. This is because solar altitude increases in summer, resulting in less solar radiation falling on the vertical surface of a building (as shown in Figure 3.1). As aforementioned, window heat gains mainly consist of transmitted solar radiation (yellow column) and secondary heat gain (orange column) shown in Figure 3.10(b).

For all TC windows excluding NVO_2_t40, it is noted that secondary solar heat gains account for a large proportion of window heat gain, ranging from 32.89% to 42.89%, during the cooling period. This, in turn, means reducing solar transmittance is not the only way to reduce cooling load in summer, lower secondary heat gain can potentially also reduce window solar heat gain. As mentioned in section 3.3.1.1, lower solar absorptance results in lower window temperature, which decreases the temperature difference between window surface and indoor temperature and hence reduces convection between the window and room space. Meanwhile, lower emissivity can reduce the long-wave radiation heat flow to the room from the indoor glass surface. Lower solar absorptance, as well as emissivity both, yield lower secondary heat gains. VO_2_t38 had the lower secondary heat gain of 68.37 W/m^2 that the other four types of TC windows (i.e. secondary heat gain ranging across 69.88-97.21 W/m^2) produce during the cooling period. This is the combined action of its relatively low solar absorptance (i.e.

0.31-0.41) and emissivity (i.e. 0.83-0.97), as shown in Table 3.2. Meanwhile, the lower secondary heat gains of VO_2_t38 reverse the disadvantage of the higher transmitted solar radiation. Therefore, regarding window heat gains, higher solar absorptance and emissivity may not be the desirable properties for TC windows in summer.

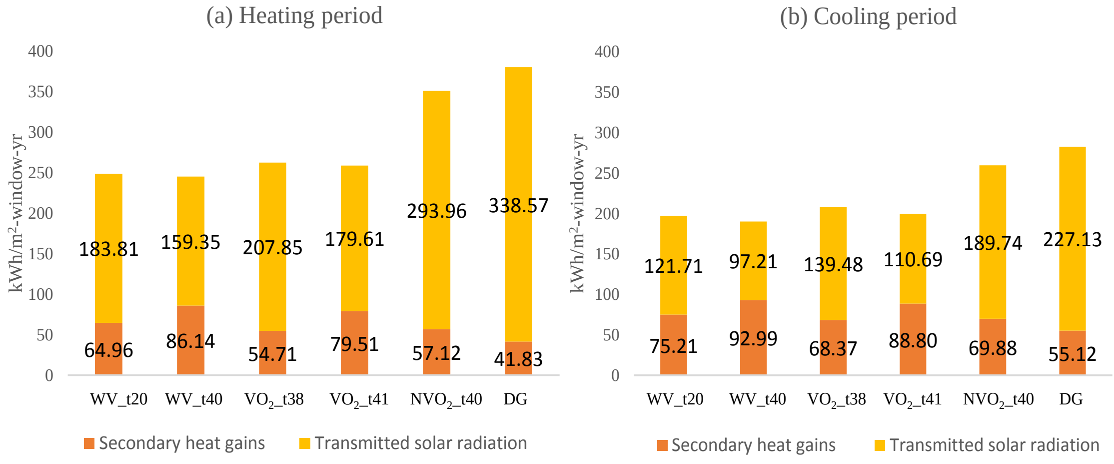


Figure 3.10: Breakdowns of window heat gains in heating and cooling periods respectively

3.3.2. Overall total energy consumption under five different climates in China

To explore the effect of TC windows on building energy performance, the total energy consumption of the office was predicted under five different climates in China, and the results can be found in Figure 3.11. Under all of the tested climatic conditions but Harbin, the TC windows result in energy saving up to 19.9% when compared with traditional clear double glazing. TC windows reduced cooling consumption, while increasing heating and lighting consumption simultaneously. However, the presence of any TC glazing gave rise to the overall energy consumption in Harbin, since the increase of heating and lighting demand countered the decrease of energy consumption caused by cooling reduction. This is because Harbin has a longer heating season period and the outdoor temperature is extremely low (i.e. the average outdoor temperature in winter is -20°C). Thus, 58% of the annual energy consumption is caused by heating for a room with traditional clear double glazing, while for the other four climates, heating consumption accounted for only up to 30%. The reduced solar transmittance of TC glazing in both S-state and M-state obstructs more solar heat gains for passive heating during the heating season, indicating that TC glazing might not be suitable to be applied in severe cold climates.

It can also be seen that the reduced cooling energy and increased heating energy caused by WV_t20, WV_t40, VO_2_t38 and VO_2_t41 are similar under five climatic conditions, although they have different transition temperatures and optical properties (see Table 3.2). For example, under Beijing's climatic condition, cooling energy is reduced by between 27.39 and 29.27% (i.e. 1.88% difference between these four types of TC windows) and heating energy is increased by between 26.86 and 31.26% (i.e. 4.4% difference) when compared with clear double glazing. VO_2_t38 showed the lowest energy consumption amongst the four types of TC glazing. Overall, energy saving caused by VO_2_t38 was 6.9% in Beijing, 9.12% in Hangzhou, 19.9% in Kunming and 13% in Guangzhou.

As can be seen, VO_2_t38 has less impact on lighting energy consumption because of its relatively high visible transmittance (51% at M-state, 61% at S-state). Among these four types of thermochromic window, WV_t20 has a relatively low transition temperature of 20°C and therefore, as expected, its tinted state is easier to achieve than the other three TCs under the same climate conditions. This would result in increased tinted hours for WV_t20 to block solar heat from being transmitted inside. However, it did not show significant benefit in terms of improving energy performance over the other three. It is mostly due to the restricted modulation of solar transmittance, which changes from 44% to 39% with temperature raising over transition temperature. Therefore, there is neither significant reduction of cooling energy on hot days nor a large increase of heating consumption on cold days. WV_t40, VO_2_t38, and VO_2_t41 have a relative larger solar transmittance reduction of 12.4%, 8.0% and 10.5% respectively. Although their tinted states are more difficult to achieve because of the higher transition temperatures (around 40^{o}C) required, their heating and cooling energy consumption are similar to that of WV_t20. This means that a higher transition temperature, which is an undesirable feature for TC materials, could be overcome by increasing solar transmittance modulation. NVO_2_t40 results in the least energy conservation of all these five TCs, ranging across 0.15%-3.02% in Beijing, Hangzhou, Kunming, and Guangzhou, when compared with clear double glazing. The reason behind the undesirable performance of NVO_2_t40 is that its solar transmittance at S-state before tinted is 69%, which is quite close to that of double glazing (78%), and its solar transmittance is 57% at M-state after tinting, which is even higher than the transmittance of the other four TC windows before tinted (i.e. 46% maximum). Hence, it did not provide sufficient reduction for the penetration of solar energy during hot days.

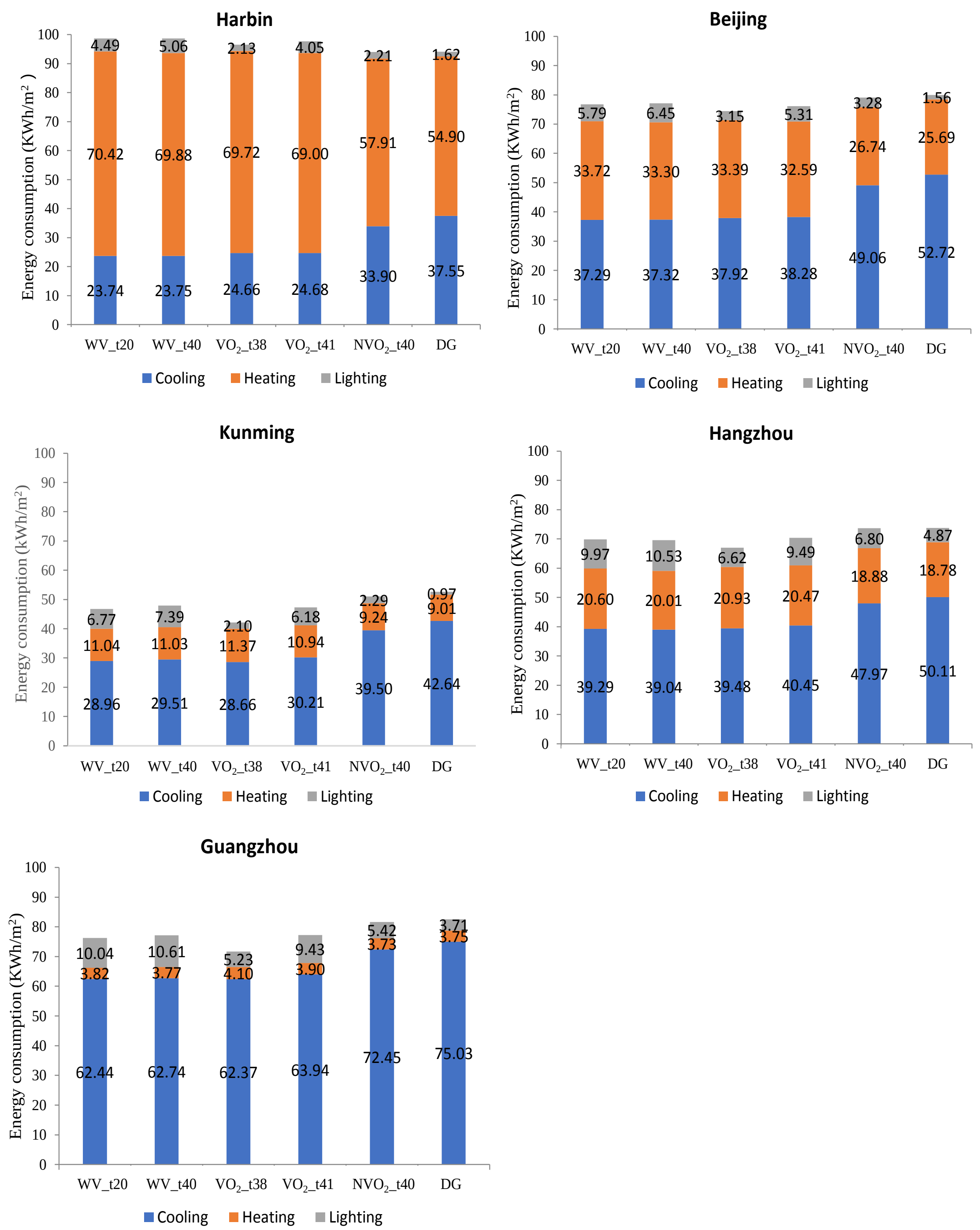


Figure 3.11: Total energy consumption of room with WWR of 60%, including heating, cooling and lighting, classified by different climatic conditions WV_t20 (Tt=20°C, Tsol 0.440 -0.390) WV_t40(Tt=40°C, Tsol 0.412 -0.39); VO_2_t38 (Tt=38.5°C, Tsol 0.460 -0.380); VO_2_t41(Tt=41.3°C, Tsol 0.44 -0.355); NVO_2_t40(Tt=40°C, Tsol 0.69 -0.57

3.3.3. The effects of thermochromic glazing on indoor daylight performance and lighting demand

Useful daylight illuminance (UDI) was used to evaluate daylight performance for reference double glazing (DG) and TC windows under five different climatic conditions. Figure 3.12 shows the predicted UDI at sensors 1 and 2 during working period, respectively. The orange, blue and grey columns represent $UDI_{0\text{-}500lux}$, $UDI_{500\text{-}2000lux}$, and $UDI_{>2000lux}$, respectively. When the illuminance is lower than 500 lux, artificial lighting is required to supplement visual comfort in the office, which means extra lighting energy will be consumed. It can be seen that the working hours falling into the undersupply $UDI_{0\text{-}500lux}$ bins of both sensor 1 and sensor 2 are increased by TC windows under all climates when compared to the use of traditional double glazing. This is because the visible transmittances of all the studied TC windows are lower than that of the traditional clear double glazing, indicating that less daylighting transmits through the windows. Oversupplied illuminance (over 2000lux) on the work plane might cause glare or overheating problems. Therefore, the values of $UDI_{>2000lux}$ should also be investigated. The simulation results present that all studied TC windows reduce the percentage of oversupply daylight hours ($UDI_{>2000lux}$) when compared with DG under all climatic conditions. Upon the dual effect of increasing undersupply daylight hours ($UDI_{0\text{-}500lux}$) and decreasing oversupply daylight hours ($UDI_{>2000lux}$) caused by the studied TC windows, the percentage of hours where UDI is the most desired range might increase or decrease when compared with DG under different climatic conditions. This has been investigated in this section. For office buildings, the desired range of illumination is from 500 lux to 2000 lux [108], where sufficient daylight without compensation from artificial lighting for working is available, meanwhile avoiding visual discomfort caused by oversupply daylighting. Figure 3.12 illustrates the annual percentage of each UDI bin for the selected glazing under the five climatic conditions.

Depending on the optical properties, the five types of TC windows were classified into two groups: The first group includes WV_t20, WV_t40, and VO_2_t41, which have relatively low visible transmittances of around 40% (Low VT group) and the other group consists of VO_2_t38 and NVO_2_t40, which have relatively higher visible transmittances of approximately 60% (High VT group). For the selected traditional DG, $UDI_{>2000lux}$ dominates for sensor 1, and $UDI_{500\text{-}2000lux}$ accounts for a large proportion for sensor 2 (i.e. 57.81-76.94%) under all climates. This means that oversupply of daylight is the main issue for the region close to the window.

For the low VT group, the working hours within the most desired range of UDI ($UDI_{500\text{-}2000lux}$) increase at sensor 1, whilst decreasing at sensor 2 when compared to that of the selected traditional glazing. Taking Beijing as an example, comparing with the reference DG, the values of UDI $_{500\text{-}2000lux}$ at sensor 1 increased by 35.08%, 39.33% and 32.21% respectively, which is dominantly caused by decreasing hours of oversupplied daylighting ($UDI_{>2000lux}$). At sensor 2, the working hours falling in the desired $UDI_{500\text{-}2000lux}$ bin are reduced under the effect of these three TC windows by 12.55%, 18.23%, and 8.4%, mostly caused by increasing percentages of undersupplied daylight hours ($UDI_{0\text{-}500lux}$), which increase from 11.71% to 48.37%, 54.05%, and 44.22% respectively.

For the high VT group, the desired daylight hours (i.e. hours in $UDI_{500\text{-}2000lux}$ bin) at both sensor 1 and sensor 2 are higher than DG. However, the increasing range at sensor 1 is 7.95% and 9.24% respectively, which is less significant than that caused by TC window in the low VT group. For sensor 2, the percentages of desired daylight ($UDI_{500\text{-}2000lux}$) increase by 2.52% and 1.83% respectively when compared with DG. This is because the increase of undersupplied daylighting hours ($UDI_{0\text{-}500lux}$) cannot reverse the upward trend of the working hours falling in the most desired daylight range ($UDI_{500\text{-}2000lux}$).

Under different climates, the distribution of UDI bins for the five TC windows changes dramatically. In the following discussion, WV_t40 is chosen as an example of the low VT group, and VO_2_t38 is selected as a representative of the high VT group. For the room with WV_t40 applied, working hours falling in desired daylight range ($UDI_{500\text{-}2000lux}$) at sensor 2 are more than that of sensor 1 under the climatic conditions of Harbin and Beijing, while in Kunming, Hangzhou, and Guangzhou, sensor 1 is reverse and has more hours within the most desired $UDI_{500\text{-}2000lux}$ bin. Additionally, when compared with DG, WV_t40 induced a significant reduction of desired daylight hours ($UDI_{500\text{-}2000lux}$) at sensor 2 with the decrease of latitude geographically. This is likely a consequence of the relationship between solar altitude and the depth that daylight can access, which means that it is more difficult for direct solar radiation to reach the working plane in the region far away from the window when solar altitude is high. Therefore a TC window with low visible transmittance blocks more accessible daylighting and aggravates this issue. For VO_2_t38, the percentage of working hours within desired daylighting range ($UDI_{500\text{-}2000lux}$) of sensor 1 is lower than that of sensor 2 under all climates. At sensor 1, the desired daylight hours ($UDI_{500\text{-}2000lux}$) are more than that of DG. For the region of sensor 2, when compared with DG, the percentage of $UDI_{500\text{-}2000lux}$ is increased by up to 15.52% in Harbin, Beijing, and Kunming, but slightly reduced by 5.04% and 1.04% respectively in Hangzhou and Guangzhou. This is also due to the relationship between solar altitude and the depth of daylighting to access, in addition to the fact that a higher solar altitude slightly reverses the upward trend of $UDI_{500\text{-}2000lux}$ at sensor 2. In conclusion, the TC windows with the higher visible transmittances could be relatively less influenced by different climates in terms of desirable daylighting availability.

To sum up, because of lower visible transmittance than standard double glazing, the TC glazing has a feature of reducing visual discomfort caused by oversupplied daylighting. The TC windows with relatively lower visible transmittance, including WV_t20, WV_t40, and NVO_2_t40, significantly improved the visual comfort levels of the region near the window (sensor 1) under all climatic conditions. However, in the region far away from the window (sensor 2), daylighting levels are sensible to climatic conditions, particular to climate with low latitude such as Hangzhou and Guangzhou, which would result in increasing the percentage of working hours within the undersupplied daylight range ($UDI_{0\text{-}500lux}$), and hence consuming extra lighting energy. The TC windows with relatively higher visible transmittances, including VO_2_t38 and NVO_2_t40, also improved visual comfort levels of the whole room under the climatic conditions of Harbin, Beijing, and Kunming. The influence of higher solar altitude in Hangzhou and Shanghai has not led to significant decrease of desired daylighting hours ($UDI_{500\text{-}2000lux}$) compared with DG. This indicates that the TC windows with higher visible transmittance are more flexible to be applied under various climates from the perspective of daylight comfort.

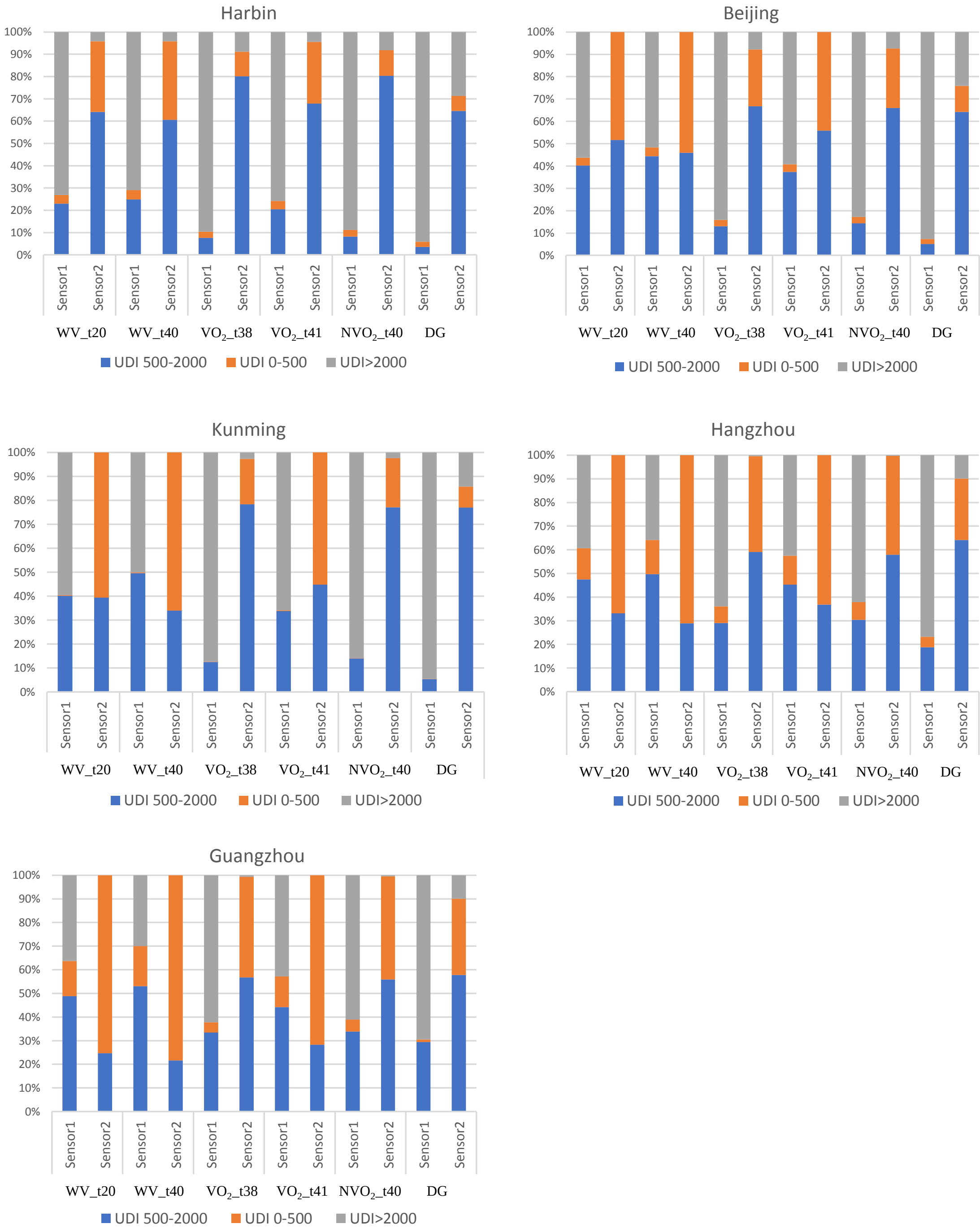


Figure 3.12: Annual percentage of $UDI_{0\text{-}500lux}$, $UDI_{500\text{-}2000lux}$ and $UDI_{>2000lux}$ levels of illuminance sensors 1 and 2 in an office room with five types of TC windows and reference DG applied respectively under five climatic conditions.

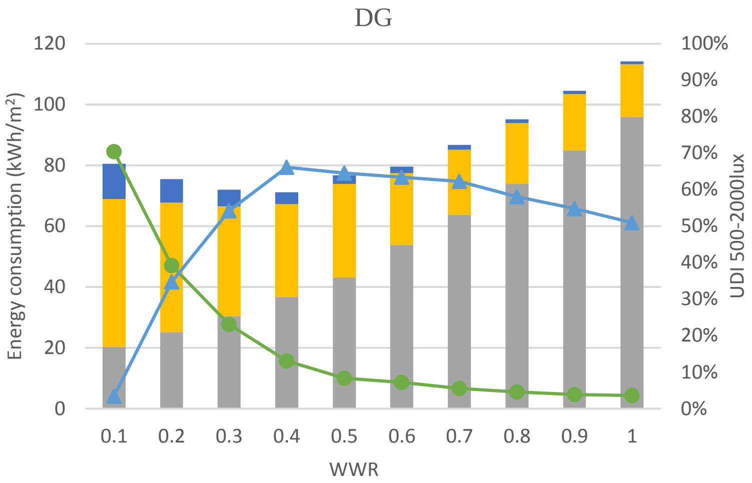
3.3.4. Effects of WWR on TC performance energy and visual comfort

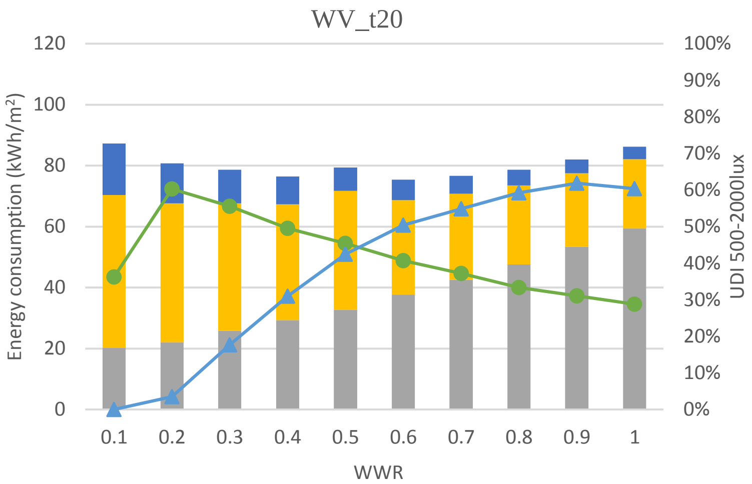
In order to explore the appropriate window size for using TC windows based on the studied office room under different climatic conditions, the simulations were conducted under ten scenarios with different window-to-wall ratios (WWRs), which ranged from 0.1 to 1 at the intervals of 0.1. The building energy consumption and annual percentage of $UDI_{500\text{-}2000lux}$ for the selected TC windows and DG window at different WWRs under Beijing's climatic condition are illustrated in Figure 3.13. Energy consumption changing with WWRs is shown in stacked bars for cooling (grey), heating (yellow), and artificial lighting energy (blue). The two curves show the values of $UDI_{500\text{-}2000lux}$ that vary with WWRs in the region close to (sensor 1) and far away (sensor 2) from the window. It must be noted that the results of this study are valid for a room with the described conditions and dimensions, with a single opening placed in the south-facing surface.

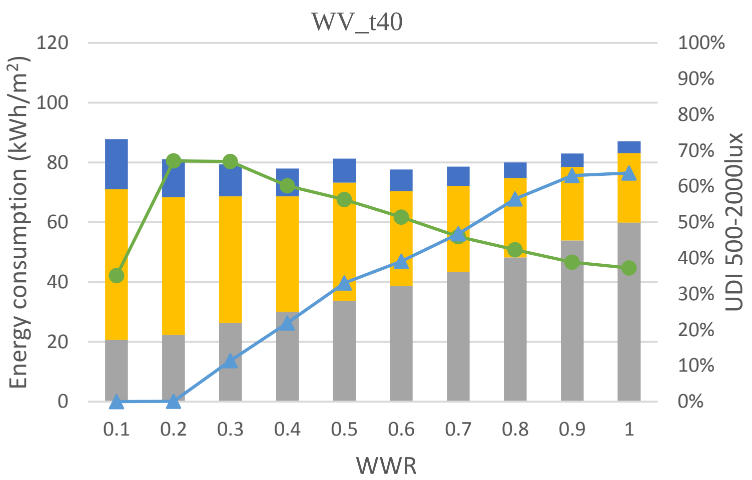
In terms of standard double glazing (DG), cooling energy consumption was found to increase with the increasing of window size (i.e. WWR increasing from 0.1 to 1), and becomes the dominant energy use. Additionally, the percentage of working hours within the desired daylight range ($UDI_{500\text{-}2000lux}$) at sensor 1 is reduced, because of more oversupplied daylight hours (>2000lux). Whereas arbitrarily reducing the WWR results in the increase of heating energy consumption and extra artificial lighting to supplement the undersupplied daylighting (<500lux). Under the same window size, the pairwise comparison between each type of TC window and the reference DG with respect to total energy consumption indicates that TC windows can only provide energy conservation for large window sizes, where cooling energy consumption is dominated. To specify the window size when energy saving could be achieved, the corresponding range of WWRs is proposed and named as energy saving range (labelled as ES). For the daylight performance, as can be seen, there is a trade-off relationship between the values of

$UDI_{500\text{-}2000lux}$ at sensor 1 and sensor 2. At the cross point of the two curves, the same percentage of working hours fall into desired daylight range for both sensors. This means oversupplied daylighting in the region close to the window caused by larger windows and undersupplied daylighting in the region far away from the window caused by smaller windows are mostly avoided. The corresponding WWR of the cross point at x-axis is defined as WWR for balanced illuminance (labelled as BI). For a particular TC window, if the WWR for balanced illuminance (BI) is in the energy-saving range (ES), both energy conservation and visual comfort can be achieved simultaneously, as is shown in Table 3.3.

As can be seen in Figure 3.13, all the studied TC windows apart from NVO_2_t40 have a similar tendency of energy consumption changing with varying window size. Taking WV_t40 as an example, when the WWR is between 0.6 and 1 (i.e. ES is also 0.6-1 for WV_t40) under the climatic conditions of Beijing, WV_t40 causes a decrease of total energy consumption ranging from 2.42% - 23.75% when compared with reference DG; Increasing window size can result in more energy conservation. The remaining four TC windows also have a similar energy saving range of 0.6-1. However, the decrease of energy consumption when applying NVO_2_t40 is less significant as the other TCs when compared with DG, which is up to 6.17%. This is consistent with the discussion conducted in section 3.3.3.


DG
Energy consumption (kWh/m²)
UDI 500-2000lux
WWR
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%


WV_t20
Energy consumption (kWh/m²)
UDI 500-2000lux
WWR
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%


WV_t40
Energy consumption (kWh/m²)
UDI 500-2000lux
WWR
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

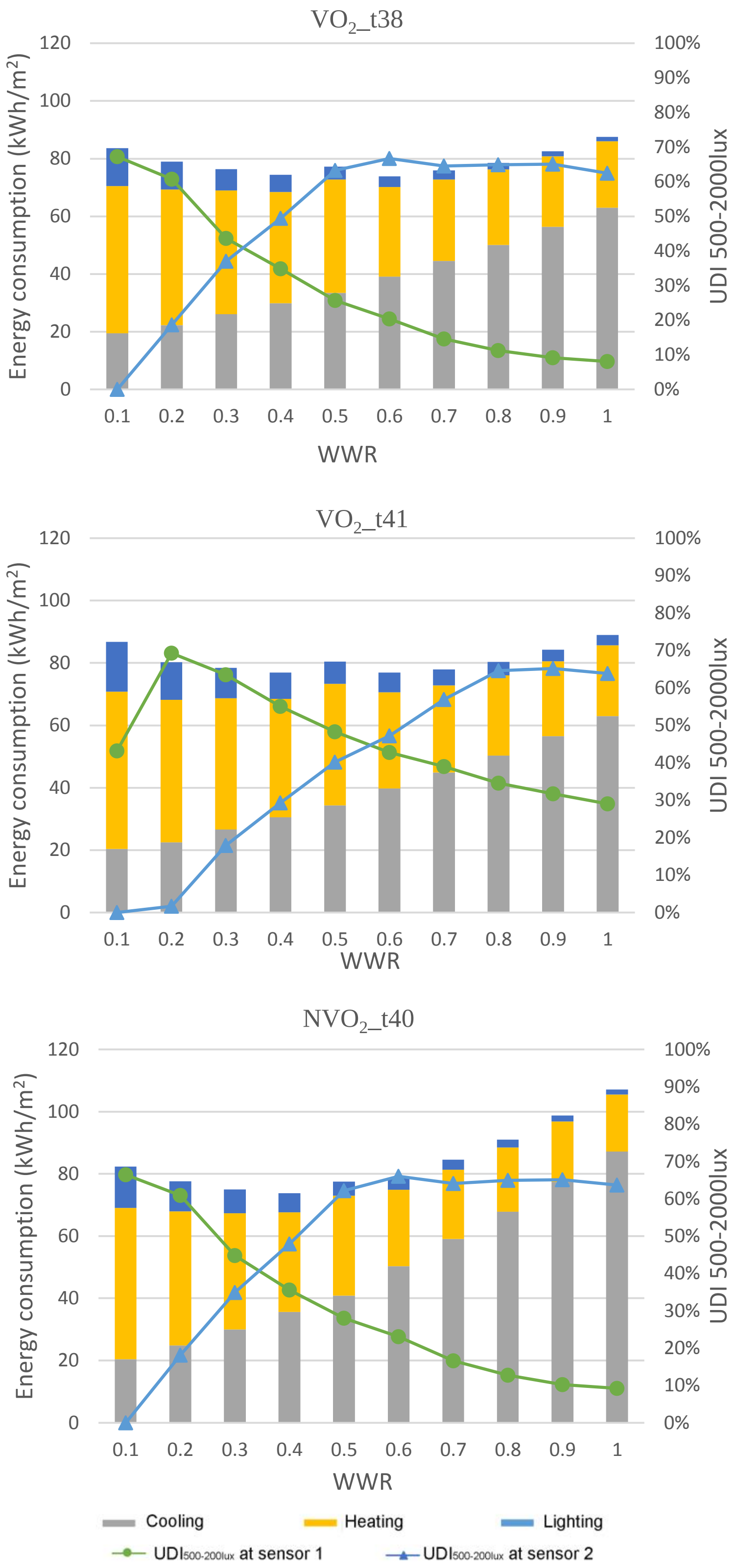


Figure 3.13: Building energy consumption and daylight performance for various TC windows at different window to wall rations under Beijing climatic condition

In terms of balanced illuminance, DG shows a cross point of $UDI_{500\text{-}2000lux}$ curves of sensor 1 and sensor 2 when the WWR is 0.2 (i.e. BI value is 0.2 for DG) under the climatic conditions of Beijing, and the corresponding desired daylight hours account for 37% of working hours (i.e. $UDI_{500\text{-}2000lux}$ for sensor 1 = $UDI_{500\text{-}2000lux}$ for sensor 2 = 37%). This means a small window size is more desirable for clear double glazing as the issue of oversupplied daylighting can be moderated. Compared with DG, all the TC windows achieve higher BI values. This can be explained by the fact that the TC windows diminish oversupplied daylighting and increase $UDI_{500\text{-}2000lux}$. For WV_t40, the balanced illuminance occurs when WWR is 0.7, and it has fallen into its energy saving range of 0.6 -1, which means that a WWR of around 0.7 is the desired window size for using WV_t40 windows in Beijing, in terms of energy saving and daylight performance improvement. For WV_t20, and NVO_2_t40, BI values were found to be 0.5 and 0.6 respectively, with a balanced $UDI_{500\text{-}2000lux}$ of around 46%. VO_2_t38 and NVO_2_t40 have lower BI values than the others of 0.3 and 0.4 respectively. The $UDI_{500\text{-}2000lux}$ values of their cross points are 40.69% and 40.14% respectively.

Table 3.3: Summarised Energy Saving range (ES) and Balanced Illuminance (BI) under the suitable window to wall ratios for five types of TC glazing and reference DG under the five selected climates respectively

	Harbin		**Beijing**		**Hangzhou**		**Kunming**		**Guangzhou**	
	ES	BI	ES	BI	ES	BI	ES	BI	ES	BI
WV_t20	0.8-1	0.5	0.6-1	0.5	0.5-1	0.7	0.5-1	0.6	0.3-1	0.6
WV_t40	0.8-1	0.5	0.6-1	0.7	0.6-1	0.9	0.6-1	0.8	0.3-1	1
VO_2_t38	0.7-1	0.3	0.6-1	0.4	0.4-1	0.5	0.3-1	0.4	0.3-1	0.5
VO_2_t41	0.7-1	0.4	0.6-1	0.6	0.6-1	0.8	0.6-1	0.7	0.3-1	0.8
NVO_2_t40	0.6-1	0.3	0.6-1	0.4	0.6-1	0.5	0.6-1	0.4	0.6-1	0.6
DG	—	0.2	—	0.2	—	0.3		0.2	—	0.4

Table 3.3 specifies the ES and BI values of five TC windows under the studied climatic conditions. As can be seen, with increasing latitudes, the ES range of all TC windows (excluding NVO_2_t40) broadens, with the maximum increase being from 0.3-1

to 0.8-1. This means that in climates with colder winter, a larger window area is required to receive more solar heat gains on cold days to make up the reduction in transmitted solar radiation caused by the TC windows. Meanwhile, BIs of all TC windows are seen to increase with a decrease in latitude, which means higher solar altitudes increase the difficulty for daylight to reach the region far away from the window. Thus a larger window size is necessary to improve daylight distribution. In addition, it can be seen that the TC windows with lower visible transmittance are more sensitive to the altitude changing, e.g. WV_t40 results in an increase of BI values ranging from 0.5 to 1 with the increase in solar altitudes. However, for VO_2_t38, which has a relatively higher visible transmittance, it is changing slightly from 0.3 to 0.5. Under the climatic conditions of Harbin, there is no BI value falling into the range ES, which means that simultaneously achieving both energy saving and desired daylight availability is difficult. On the contrary, in Guangzhou, the BIs of all studied TC windows are within their corresponding energy saving ranges respectively, which means that every TC window has the potential to attain energy efficient and desirable daylight availability at the same time by using an appropriate window size. For Hangzhou and Kunming, all TCs except NVO_2_t40 has BI fall within the range of ES. For Beijing, only limited types of TC windows (i.e. WV_t40 and NVO_2_t40) have this appropriate window size for improving both enegy and daylighting performance in a building. This indicates that TC windows are more flexible to be used under climatic conditions with lower latitudes, and have more cooling demand.

3.4. Summary

VO_2-based thermochromic materials have potential to improve both building energy performance and visual comfort compared with standard double glazing. This research conducted a comprehensive analysis method for five types of well-developed thermochromic windows with different transition temperatures and optical properties under five representative climatic conditions in China. Based on a building simulation for a typical office room in EnergyPlus, the thermal and optical behaviours of all the studied TC windows and their influence on building energy consumption and daylight performance were investigated. The following conclusions can be drawn:

1) Lowering transition temperature is not an essential requirement for applying TC windows to buildings, which may bring undesirable tinted hours on cold days leading to increasing heating energy consumption. Enlarging the change of solar transmittance has the potential to be relatively more efficient to attain desirable thermochromic performance.
2) The TC layer temperature depends on a combined effect of the solar absorptance of window alongside ambient conditions (including ambient temperature and incident solar radiation intensity). TC windows with relatively lower absorptance and higher transition temperatures such as VO_2_t38 and NVO_2_t40 required higher ambient temperature and solar radiation to trigger the transition.
3) The thermochromic glazing mainly provides energy saving by reducing the cooling demand of the building. Thus, the severe cold zone in China, where heating consumption dominated, would not be an appropriate climatic condition to use TC windows. All five types of thermochromic glazing, excluding NVO_2_t40, have similar heating and cooling energy performance, however, the lower lighting energy consumption of VO_2_t38 results in the most significant energy conservation when compared with clear double glazing.
4) For daylighting availability, all types of thermochromic glazing were shown to lead to an increase in desired annual daylight hours within $UDI_{500\text{-}2000lux}$, in the region near the window (sensor 1). In the region far away from the window (sensor 2), the desired

$UDI_{500\text{-}2000lux}$ is significantly reduced by TC windows due to lower visible transmittances, and this reduction increases with the increase of solar altitudes.

5) Considering the appropriate window-to-wall ratio for using a particular thermochromic window, results show that under the climatic conditions of Hangzhou, Kunming and Guangzhou, most types of thermochromic glazing had the potential to achieve both energy saving and desired daylight simultaneously. However, there are limited types of thermochromic glazing which could also achieve both energy saving and desired daylight under colder climates such as that of Beijing and Harbin.

This study has investigated the building energy performance and daylight availability affected by different types of TC windows under different climatic conditions, with results valid for the room with specified conditions and dimensions. The material properties (i.e. transition temperature, absorptance, modulation of solar transmittance, etc.) that would influence the performance of using TC windows have been briefly discussed, however further research about their particular influence will be conducted in following studies.

Chapter 4

Further evaluation of TC windows for energy efficient design and daylight control

4.1 Introduction

Daylight penetrates through a window system offers heat gains and illumination to the indoor environment of a building. The quality and intensity of solar radiation significantly affect the energy consumption of heating, cooling, and lighting. They also provide thermal and visual comfort for occupants in a building [109-111]. A daylit indoor space not only enable energy conservation, but also be beneficial for the mood, fatigue relieving, higher productivity, and human health [112, 113]. However, some penetrated solar radiation through windows is not desirable, e.g., during hot days and less solar radiation is required into the building to avoid overheating, but sufficient daylighting is desirable to supply artificial lighting. In cold days, more transmitted solar radiation is desired to heat up the indoor space, and reduce heating energy demand, however, resulting in oversupply daylighting, which is likely to cause visual discomfort problem. Therefore, it is increasingly essential to have a proper design of window system, to attain a balanced between thermal and visual comfort, as well as energy efficiency.

Among the traditional technologies used to control solar radiation admitted into the building, shading devices are most commonly used [114, 115]. Fixed shading devices (passive) [114, 116, 117], and moveable shading devices (active) [118-121] are the two main categories. Fixed shading devices block the solar radiation coming into the building, decreasing glare and cooling loads on hot days. Meanwhile, they block the solar heat gains required in cold days, as well as the desired daylighting, resulting in more artificial lighting. Moveable shading devices can be adjusted manually or automatically, and block the undesirable daylighting dynamically. However, it is the full-spectrum solar radiation that is reduced by shading devices, a compromise on daylighting or energy saving has to be selected.

Thus, tinted glazing [122], reflective glazing [123], anti-reflective coated glazing [124], and low-e coating glazing [7] were developed to effectively reduce oversupplied daylighting (i.e., mainly caused by visible spectrum) or solar heat gains (i.e., mainly caused by NIR spectrum). Although these coatings have the features of spectrum selectivity, i.e., admitting specific wavelength range of solar radiation and block the remaining, it is still difficult to meet the varying climatic conditions, since the spectral selectivity is static.

To provide high performance of solar heat gain and daylighting control, a variety of glazing technologies have been developed. Chromogenic smart windows consist of different types depending on their stimulus, they all have at least two states, which are before and after being stimulated. After being stimulated, the chromogenic smart window could change their visible or NIR transmittance properties, obtaining a desired daylighting level and thermal comfort inside the building respectively, the stimulus could be heat, electricity, light, and gas [100]. Also, liquid crystals and suspended particle devices are the other two types of smart glazing, which performs similarly to electrochromic windows (chromogenic smart windows whose stimulus is electricity) [125].

As mentioned in Chapter 3, some studies have proved that VO_2-based TC glazing has the advantages to improve energy efficient and thermal comfort especially in hot climates [12, 14-16, 98]. However, the daylighting performance affected by TC windows has rarely been discussed. Most of the previous studies indicated that one of the advantages of VO_2-based TC materials is maintaining the transmittance of visible spectrum during the transition [86, 126, 127]. Additionally, their visible transmittance was considered too low (~40%), which required being improved. However, the enlarging glazing area has become a trend of architecture design, especially for commercial buildings. On the other hand, daylight varies depending on geographical latitude, sky conditions, time of the year and day[109]. Based on the results in chapter 3, VO_2-based TC windows could be more energy efficient in the room with larger window size. All these support that maintaining a high transmittance of visible solar radiation might fail to meet the requirement of visual comfort indoors.

In order to realize the adjustment of visible transmittance, and improve the performance of TC glazing studied in chapter 3, an innovative iron-liquid based complex film produced by Wei *et al*. [9] was studied in this work. It is also thermochromic and has the capacity of reducing visible transmittance with a temperature rising. Meanwhile, its colour changes from clear to blue. In this chapter, further simulation of TC windows applied in buildings was conducted, to explore the potential development of TC materials and application methods. Both VO_2-based and iron-liquid based TC materials were investigated within three scenarios: 1) effect of transition temperatures on both TC performance; 2) effect of improving the properties of visible and NIR transmittance respectively; 3) different cases of cooperation between the two types of TC films, realizing the adjustment of both visible and NIR spectrum. The scenarios were carried out under three different climates. Depending on the features of different climates, the specific requirement of TC window for each climate was proposed to be analysed.

4.2. Methodology

Based on the typical office modelling in EnergyPlus, three scenarios of TC windows were installed in three typical climates of China were used to conduct the simulation, which have different climatic characteristics and meanwhile are suitable to be use TC windows. It aims to explore the potential development of TC windows for energy efficiency and daylight control.

4.2.1. Climates

IWEC (International Weather for Energy Calculation) weather file of Beijing, Shanghai, and Guangzhou respectively was used to conduct this simulation with 15mins per time step for a whole year. They are representative climatic conditions of three different zones in China, i.e. Beijing stands for the cold zone, Shanghai for the hot summer and cold winter zone, and Guangzhou for the hot summer and warm winter zone. These three climates all have hot summer with average temperature in the hottest month ranging from 25-30°C. Meanwhile, Beijing has both distinct cold and hot days during a year, and the lowest average temperature in winter is -2.9°C. Guangzhou is a city with hot summer (maximum 35°C) and warm winter (minimum 6.6°C). Shanghai has a mediate winter of around 5°C, which is warmer than Beijing and colder than Guangzhou. In addition, the three cities are located at a different latitude, therefore, resulting in different solar incidence angles, and the maximum angle is approximately 70° in Beijing, 80° for Shanghai, and 90° in Guangzhou. A higher solar incident angle means more difficulties for solar radiation approaching the region far away from the vertical window in a building, and less incident solar radiation on the vertical surface.

4.2.2. EnergyPlus model setting up

The setting up of model used in this study is same as that in Chapter 3, section 3.2.2.1. Simulations in this chapter based on two selected TC materials: 1) VO_2 nanoparticle (i.e., VO_2_Nano) films has the feature of apparent reducing the NIR spectrum of transmitted solar radiation(τ_{NIR}) at the temperature above its transition temperature (T_t ~60°C), while with a slight decrease of visible spectrum transmitted [8]. 2) a composite film of Ionic-liquid containing $[bmim]_2$ $NiCl_4$ (i.e., TC_IL-Ni^{II}), which generally has the capable of change the visible transmittance (τ_{vis}) with temperature changing across 25-75°C [9].

Three scenarios were conducted by EnergyPlus simulaiton, to explore the best performance when they were applied as TC windows, covering the variation of T_t, enlarging the change of τ_{vis} for TC_IL-Ni^{II} and τ_{NIR} for VO_2_Nano, as well as the different combination of TC window films.

4.2.2.1 Scenario I

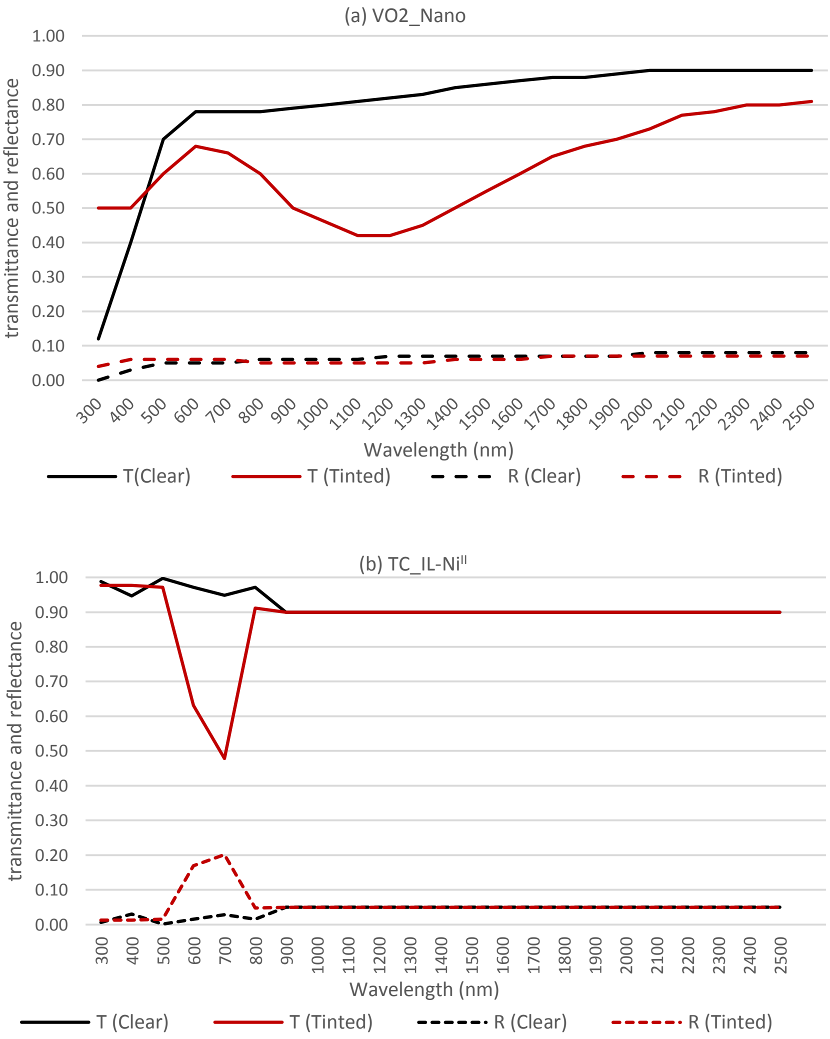


Figure 4.1: Spectral transmittance and reflectance of VO_2_Nano and TC_IL-Ni^{II}, different transition temperatures were set to 20, 25, 30, 35 and 40 ºC**.**

In this scenario, transition temperatures of the two typical thermochromic materials that affect building energy and daylighting performance were studied. Figure 4.1 shows the spectral transmittance and reflectance of practical VO_2_Nano and TC_IL-Ni^{II} coating films. Each of them was coated on the inner surface of outside glazing pane within the double-glazing window system. Simulations were conducted across different transition temperatures of both TC windows with a transition temperature of 20, 25, 30, 35, and 40°C, respectively.

4.2.2.2. Scenario II

The practical VO_2_Nano and TC_IL-Ni^{II} films are facing the common problem of restricted energy saving and daylighting adjustment, respectively [9, 128]. The reason that caused this limitation is their high τ_{NIR} and τ_{vis} at clear state, but limited the reduction of NIR transmittance and visible transmittance at tinted state. Thus, a theoretical energy efficiency strategy of improving NIR transmittance and visible transmittance has been proposed and analysed in this scenario. The performance of VO_2_Nano window with improved NIR transmittance, and TC_IL-Ni^{II} window with improved visible transmittance were simulated. Meanwhile, the transition temperatures of 20, 30 and 40°C were assigned to each improved TC windows, respectively, in order to explore whether the most appropriate transition temperature discussed in the scenario I would be affected by improved optical properties of TC windows. Figure 4.2 and Table 4.1 present the transmittance variations of both TC materials.

For VO_2_Nano, two types of improved VO_2_Nano film has optical properties of Tinted_M and Tinted_L at tinted state, but the same solar transmittance (τ_{sol}) of 0.692 at clear state, with spectral transmittance shown T (clear) in Figure 4.2(a). Tinted_M has a moderate reduction of NIR transmittance, and the same τ_{vis} as original VO_2_Nano at tinted state, resulting in solar transmittance of 0.516. While Tint_L has a large reduction of NIR transmittance at tinted state, resulting in a solar transmittance of 0.385. It is assumed that the original solar absorptance (α) of VO_2_Nano is constant, which is 0.235

at clear state and 0.247 at every tinted state. This means that the reduction of solar transmittance is mainly caused by increasing solar reflectance.

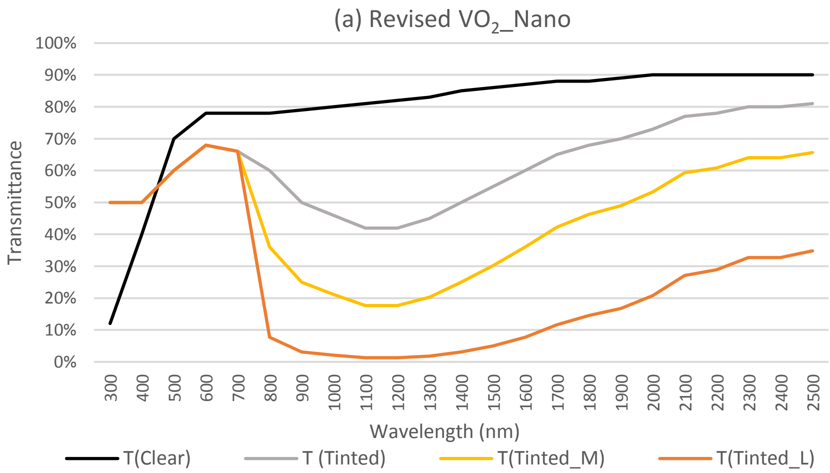
TC_IL-Ni^{II} also has two types of improved Tinted_M (τ_{sol}=0.770) and Tinted_L (τ_{sol}=0.631) at tinted state, and same optical properties at cleat state (τ_{sol}=0.948), as is shown in Figure 4.2 (b). However, the change of solar transmittance is mainly caused by the reduction of visible transmittance at tinted state.

It can be seen that, the changes of solar transmittance ($\Delta\tau_{sol}$) after TC transition of improved VO_2_Nano and TC_IL-Ni^{II} are similar to each other, i.e., the two types of TC films have similar $\Delta\tau_{sol} \approx 0.18$ when changing to Tinted_M state, and similar $\Delta\tau_{sol} \approx 0.30$ for changing to Tint_L state. Additionally, their absorptance were assumed to be as original TC_IL-Ni^{II} film as well, which are 0.025 at clear state and 0.086 at tinted state.

Both types of revised VO_2_Nano were assumed to have the same absorptance as the original material of VO_2_Nano, which is 0.235 at clear state, and 0.247 at tinted state, which means that increasing solar reflection causes the reduction of solar transmittance.

Table 4.1: Spectral properties of original and revised VO_2_Nano and TC_IL-Ni^{II}

	VO_2_Nano				**TC_IL-Ni ^{II}**			
	Clear	Tinted	Tinted_M	Tinted_L	Clear	Tinted	Tinted_M	Tinted_L
Solar transmittance (τ_{sol})	0.692	0.571	0.516	0.385	0.948	0.844	0.770	0.631
NIR transmittance (τ_{NIR})	0.819	0.533	0.394	0.062	0.914	0.902	0.890	0.826
Visible transmittance (τ_{vis})	0.656	0.605	0.605	0.605	0.968	0.790	0.669	0.471
Absorptance (α)	0.235	0.247	0.247	0.247	0.025	0.086	0.086	0.086



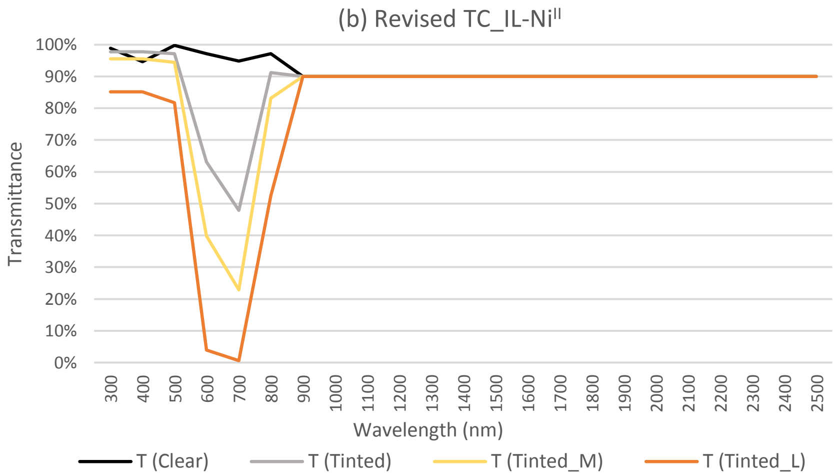


Figure 4.2: Spectral transmittance of improved VO_2_Nano (a) and TC_IL-Ni^{II} (b) with further reduced transmittance.

4.2.2.3 Scenario III

In this scenario, the approaches of cooperating between VO_2_Nano and TC_IL-Ni^{II} were explored. Based on the results of scenario II, the improved VO_2_Nano and TC_IL-Ni^{II} with larger reduction of solar transmittance led to more significant improvement of energy and daylight performance, i.e. the cases with optical properties of Tinted_L for both TC windows. Therefore, VO_2_Nano and TC_IL-Ni^{II} windows with their Tinted_L properties respectively were employed in this study.

Since the TC windows are temperature-dependent, the pairwise cooperation between VO_2_Nano and TC_IL-Ni^{II} films was designed across the three transition temperatures of 20, 30 and 40°C, respectively. Therefore, 3×3 matrix permutations resulted in 9 pairs of cooperation in total, and were classified into three groups:

1) VO_2_Nano and TC_IL-Ni^{II} have the same transition temperatures of 20°C (Same Tt20), 30°C (Same Tt30), and 40°C (Same Tt40);

2) VO_2_Nano has lower transition temperatures than that of TC_IL-Ni^{II}, which means that in the process of the temperature increasing, NIR transmittance would decrease firstly, and then visible transmittance decreases at a higher temperature. For instance, the pairwise cooperation between VO_2_Nano with T_t of 20°C and TC_IL-Ni^{II} with Tt of 30°C, was named as 'NIR_20 VIS_30'. Thus the cooperative pairs include 'NIR_20 VIS_30', 'NIR_20 VIS_40', and 'NIR_20 VIS_40'.

3) TC_IL-Ni^{II} has lower transition temperatures than that of VO_2_Nano, which means that with the temperature increasing, VIS transmittance decreases firstly, and then NIR transmittance will decrease at a higher temperature. According to the same naming rules as the group 2, the cooperative pairs include 'VIS_20 NIR_30', 'VIS_20 NIR_40', and 'VIS_20 NIR_40'.

4.3 Results and discussion

Under the three typical climatic conditions in China, building energy consumption (i.e., heating, cooling, and lighting) and daylighting performance (i.e. useful daylighting illuminance (UDI)) affected by different scenarios were investigated. Additionally, the balance between energy-saving and daylight availability were discussed, considering the specific climatic conditions, the most appropriate approaches to use TC windows in buildings would be proposed.

4.3.1. Scenario I

4.3.1.1. Energy performance

To explore the influence of TC windows with different transition temperatures on energy performance, the energy performance of the office under the selected three climates in China has been predicted by simulation, and results are shown in Figure 4.3. It can be seen that both TC windows with VO_2_Nano and TC_IL-Ni^{II} could reduce the total energy consumption when compared with clear double glazing (DG) under all three climates. It is also found that reduced cooling demand mainly causes the energy conservation, and the lower transition temperature results in lower cooling energy consumption. Moreover, at every transition temperature, TC window with VO_2_Nano results in more energy saving than that of TC_IL-Ni^{II}, and the difference of their energy saving potential is up to 5.76% in Beijing, 6.34% in Shanghai, and 7.20% in Guangzhou, which can be seen in Table 4.2.

Table 4.2: Summary of energy saving percentage caused by TC windows compared with double glazing

	Energy Saving compared with DG				
	Tt20	**Tt25**	**Tt30**	**Tt35**	**Tt40**
			Beijing		
VO_2_Nano	9.68%	10.29%	10.70%*	10.44%	9.22%
TC_IL-Ni^{II}	7.47%*	7.13%	6.03%	4.68%	3.63%
			Shanghai		
VO_2_Nano	11.00%	11.31%	11.39%*	10.73%	9.72%
TC_IL-Ni^{II}	6.98%*	6.50%	5.51%	4.54%	3.38%
			Guangzhou		
VO_2_Nano	10.67%	10.95%	11.45%	11.49%*	10.36%
TC_IL-Ni^{II}	6.20%*	6.15%	5.80%	4.61%	3.16%

*** The most significant energy saving percentage**

For the VO_2_Nano window cases (see Figure 4.3 (a) (c) and (e)), it is noted that both high (40°C) and low (20°C) transition temperature results in higher energy consumption, although the variation of energy consumption across different transition temperatures is insignificant. The transition temperatures of VO_2_Nano, which lead to a maximum energy saving, have a high correlation with climatic conditions. Results show that in Beijing and Shanghai, the maximum energy saving for the VO_2_Nano windows is achieved at the T_t of 30°C. While in Guangzhou, the most desired transition temperature of VO_2_Nano window is 35°C.

Figure 4.3 (c) (e) shows the energy consumption for the VO_2_Nano windows having different transition temperatures in Shanghai and Guangzhou. When transition temperature is low (i.e., 20 or 25°C), it is mainly the increase of lighting energy demand that diminishes the energy saving caused by less cooling energy demand, compared with DG. In Beijing (Figure 4.3 (a)), it is the increase in heating demand that reduces the energy saving at a lower transition temperature. The moderate transition temperature of 30 or 35°C enables VO_2_Nano window to reach the maximum energy saving compared with DG. It is because that the transition temperature lower than 30 or 35°C, might result in the VO_2_Nano windows having more hours spent at tinted state, even in cold days. It reveals that the VO_2_Nano windows would have a relatively lower solar transmittance for a long period. That, therefore, is likely to block the desired solar heat gains in heating demand period, as well as daylighting. On the other hand, transition temperature higher than 30 or 35°C would lead to fewer hours at tinted state, and diminish the capacity of solar spectrum control.

For the window with TC_IL-Ni^{II}, shown in Figure 4.3 (b) (d) (f), lowering transition temperature from 40 to 20°C results in the decrease of total energy consumption. It is because of the corresponding increase of heating and lighting energy have not countered the decrease of energy consumption due to cooling reduction. Thus, under all three climates, the maximum energy saving caused by the TC_IL-Ni^{II} windows compared with DG is achieved at a transition temperature of 20°C or less. These results reveal that TC_IL-Ni^{II} window has a relatively high solar transmittance (i.e., 0.948 at clear state, 0.844 at tinted state) that limit the reduction of transmitted solar radiation, therefore, the further reduced transmittance is required to achieve more significant energy saving

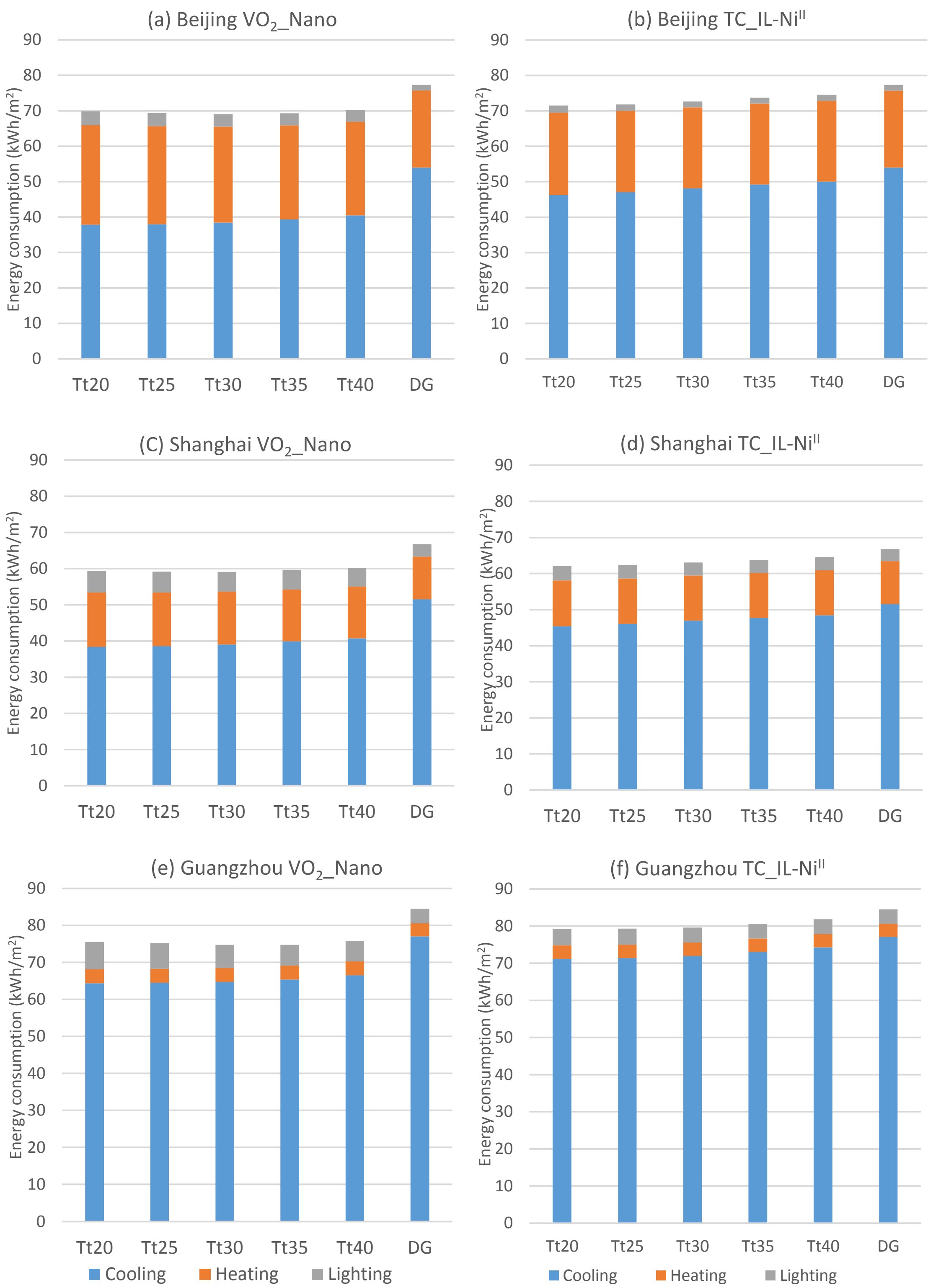


Figure 4.3. Total energy consumption including heating, cooling, and lighting, classified by windows with different TC materials (i.e., VO_2_Nano and TC_IL-Ni^{II}) and climates (i.e., Beijing, Shanghai and Guangzhou)

4.3.1.2. Daylighting performance

As aforementioned in chapter 3, $UDI_{500\text{-}2000lux}$ was reported to be the most desirable illuminance range for working environment, no artificial lighting or shading is required. However, both $UDI_{<500lux}$ and $UDI_{>2000lux}$ are proposed to be reduced, since undersupply daylight leads to more artificial lighting demand, while oversupply daylight is likely to cause visual or thermal discomfort.

Figure 4.4 shows the predicted UDI at sensor1 (i.e., region near the window). It can be seen that oversupplied daylighting, i.e., a higher percentage of working hours within oversupply $UDI_{>2000lux}$, is the main problem for the region near the window. Both types of TC windows lead to a decrease of $UDI_{>2000lux}$ and increase of $UDI_{500\text{-}2000lux}$ and due to their lower solar transmittance than DG. Meanwhile, with the decreasing of transition temperatures, more working hours falling in $UDI_{500\text{-}2000lux}$ bin was detected. It is noted that, a TC_IL-Ni^{II} window results in fewer hours within the $UDI_{500\text{-}2000lux}$ bin than that of a VO_2_Nano window when they have same transition temperatures. Both of TC windows lead to a higher $UDI_{500\text{-}2000lux}$ level with decreasing transition temperatures. The VO_2_Nano windows lead to the maximum 15% increase of working hours falling into $UDI_{500\text{-}2000lux}$ bin, compared with DG, in Beijing, and 27.42% in Shanghai, but only 6.77% in Guangzhou. While under the influence of TC_IL-Ni^{II} window, increase of $UDI_{500\text{-}2000lux}$ compared with DG is restricted, i.e., up to 3.26%. It is because that the TC_IL-Ni^{II} film has a relatively high visible transmittance (0.968 at clear state, and 0.790 at tinted state). It means that the visible transmittance of double glazing with TC_IL-Ni^{II} is similar as reference DG. A 17.8% reduction of visible transmittance is not effective to reduce hours falling into the oversupplied $UDI_{>2000lux}$ bin

Figure 4.4: Annual UDI$_{<500lux}$, UDI$_{500\text{-}2000lux}$, and UDI$_{>2000lux}$ levels at the sensor 1 affected by VO_2_Nano and TC_IL-Ni^{II} TC windows with transition temperatures across 20-40 °C under different climates.

These results indicated that the lower visible transmittance and transition temperature are both required to improve the daylighting performance of region near the window (Sensor I).

4.3.2. Scenario II

According to the results of scenario I, the effect of the original VO_2_Nano and TC_IL-Ni^{II} films have restricted TC changes on solar transmittance, which limit the capacity of energy conservation. In this section, the improved VO_2_Nano and TC_IL-Ni^{II} windows with further reduced NIR transmittance and visible transmittance at tinted states were investigated. Additionally, the most proper transition temperatures affected by the enlarged changes of solar transmittance were explored.

4.3.2.1. VO_2_Nano cases

Figure 4.5 presents the predicted energy consumption (see Figure 4.5(a) (c) (e)) and UDI levels (see Figure 4.5(b) (d) (f)) affected by improved VO_2_Nano windows with properties of Tinted_M and Tinted_L at tinted state, respectively, under the Tt of 20, 30 and 40°C. Two categories were classified:

1) Tint_M cases: VO_2_Nano with moderate reduction of NIR transmittance, the cases are named as ‘Tt20 Tint_M’ ‘Tt30 Tint_M’ and ‘Tt40 Tint_M’ according to different transition temperatures;

2) Tint_L cases: VO_2_Nano with large reduction of NIR transmittance, and the cases are named as ‘Tt20 Tint_L’ ‘Tt30 Tint_L’ and ‘Tt40 Tint_L’ respectively.

As can be seen in Figure 4.5 (a) (c) and (e), Tint_L cases were more energy efficient than Tint_M cases at every transition temperature, which is mainly caused by less cooling energy consumption. For Tint_M cases, the maximum energy conversation compared with DG is achieved at the transition temperature of 30°C, under all three climates, resulting in energy saving of 12.6 % in Beijing, 13.0 % in Shanghai, and 13.9% in Guangzhou. For Tint_L cases, the highest energy reduction as compared with DG is obtained at the transition temperature of 30°C in Beijing (16.9%) and Shanghai (17.6%), while at the transition temperature of 20°C in Guangzhou (16.0%). This means that enlarging the reduction of NIR transmittance at tinted state enables the improvement of energy performance. Therefore, the most optimal transition temperature is 30°C in Beijing and Shanghai, consistant with the results of scenario I. However, in Guangzhou, the most optimal transition temperature varies a lot according to the variation of optical properties, i.e., 35°C in the scenario I, 30°C for Tint_M cases, and 20°C for Tint_L cases. Referring to Figure 4.5 (e) and 4.3 (e), it is found that, with the enlarging reduction of NIR transmittance, more energy saving for cooling was achieved in Guangzhou, which counterbalanced the negative effect caused by increasing lighting demand for VO_2_Nano with a lower transition temperature.

Regarding daylighting performance, Figure 4.5 (b) (d) and (f) show that the UDI bins distribution of Tint_M cases have no difference from that of Tint_L when they have same transition temperature. However, the lower transition temperature results in increasing number of working hours falling within 500-2000lux (i.e., the desired $UDI_{500\text{-}2000lux}$), since a lower transition temperature is easily achieved, inducing more hours at tinted states with relative lower visible transmittance. Therefore, the reduced visible transmittance at tinted state could address the problem caused by oversupplied daylighting in the region near the window (sensor 1), and this trend is consistent with the scenario I as well. Whereas, considering the increasing lighting consumption at the lower T_t, a balance between energy and daylighting performance is proposed in the following section 4.3.3.

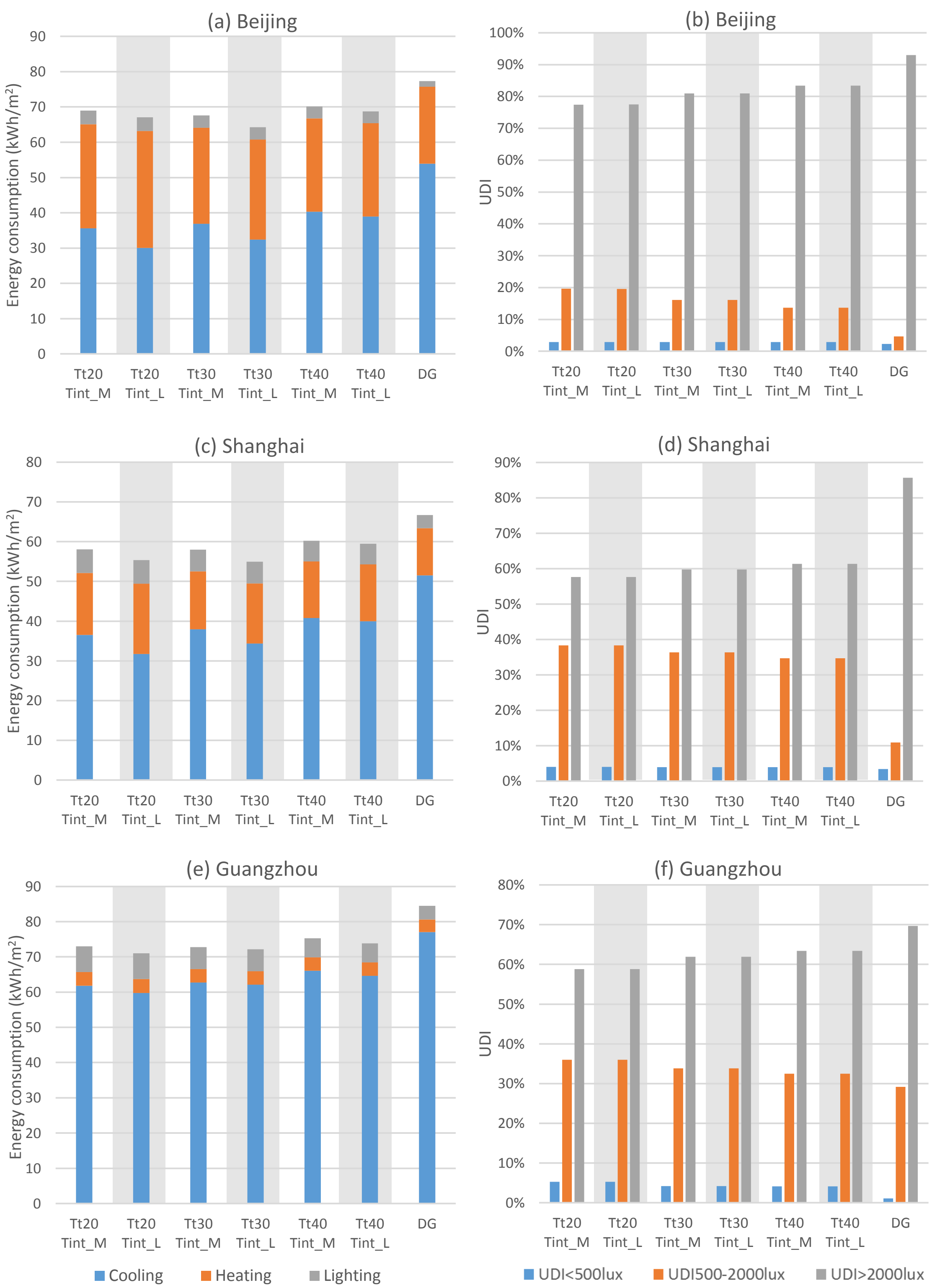


Figure 4.5. Energy consumption and annual UDI levels at sensor I affected by VO_2_Nano TC windows with different transition temperatures and lower NIR transmittance at tinted state under three climates

4.3.2.2. TC_IL-Ni^{II} cases

Different from VO_2_Nano windows, TC_IL-Ni^{II} has a significant capacity of adjusting the transmittance within the visible spectrum. Figure 4.6 illustrates the energy (Figure 4.6 (a) (c) (e)) and daylighting performance (Figure 4.6 (b) (d) (f)) affected by improved TC_IL-Ni^{II} with a transition temperature of 20, 30, and 40°C under three climates, respectively. the improved TC_IL-Ni^{II} windows are classified into:

1) Tint_M cases: TC_IL-Ni^{II} with moderate reduction of visible transmittance, the cases are named as 'Tt20 Tint_M' 'Tt30 Tint_M' and 'Tt40 Tint_M' according to different transition temperature;

2) Tint_L cases: TC_IL-Ni^{II} with a large reduction of visible transmittance, and the cases include 'Tt20 Tint_L' 'Tt30 Tint_L' and 'Tt40 Tint_L' respectively.

Figure 4.6 (a) (c) and (e) show that Tint_L cases lead to lower energy consumption than Tint_M cases at the same transition temperature. For Tint_M cases, a transition temperature of 20°C is the most optimal transition temperature for reaching the maximum energy saving under all three climates respectively, and energy reduction accounts for 9.9% in Beijing, 9.4% in Shanghai, and 8.1% in Guangzhou. For the Tint_L cases, the most energy efficient cases occur at the transition temperature of 20°C, which has total energy saving of 12.46% in Beijing, and 11.97% in Shanghai. However, in Guangzhou, the most optimal transition temperature is 30°C with an energy saving of 10.6%, with an energy reduction of 10.6% compared with DG. It is because the large reduction of visible transmittance, which blocked the daylighting, and aggravated the increase of lighting energy consumption at the lower transition temperature.

Figure 4.6 (b) (d) and (f) present that, the percentage of working hours falling into the desired $UDI_{500\text{-}2000lux}$ bins increases with the decreasing transition temperature of

Tint_M and Tint_L cases, respectively. Moreover, at the Tt of 20°C, the Tint_L cases have the highest percentage of working hours within 500-2000lux under all three climates. Compared with that of DG, the maximum increase of $UDI_{500\text{-}2000lux}$ is approximately 14% in Beijing, 22% in Shanghai, and 12% in Guangzhou. Combining the results of energy performance, the TC_IL-Ni^{II} windows within the Tint_L cases have the potential to obtain the most significant improvement of energy and daylighting performance in Beijing and Shanghai, when the transition temperature is no more than 20°C. In Guangzhou, although the case with the most energy saving is Tt30 Tint_L, Tt20 Tint_L as the secondary energy efficient one has a slightly higher energy consumption by 1.45%. This means that 20°C also has the potential to be the most proper transition temperature for Tint_L cases.

4.3.2.3. Summary

To sum up, the Tint_L cases for VO_2_Nano and TC_IL-Ni^{II} windows with improved control of NIR and visible transmittance led to lower energy consumption. VO_2_Nano windows required a higher transition temperature and induced more energy saving than TC_IL-Ni^{II} windows, but had limited capacity of adjusting daylighting. While improving the visible transmittance reduction for the TC_IL-Ni^{II} windows could result in an apparent increase in percentage of the desired $UDI_{500\text{-}2000lux}$. However, because of the high visible transmittance ($\tau_{vis} \approx 97\%$) of the TC_IL-Ni^{II} film at the clear state, the absolute values of $UDI_{500\text{-}2000lux}$ affected by the TC_IL-Ni^{II} windows are lower than that of VO_2_Nano windows.

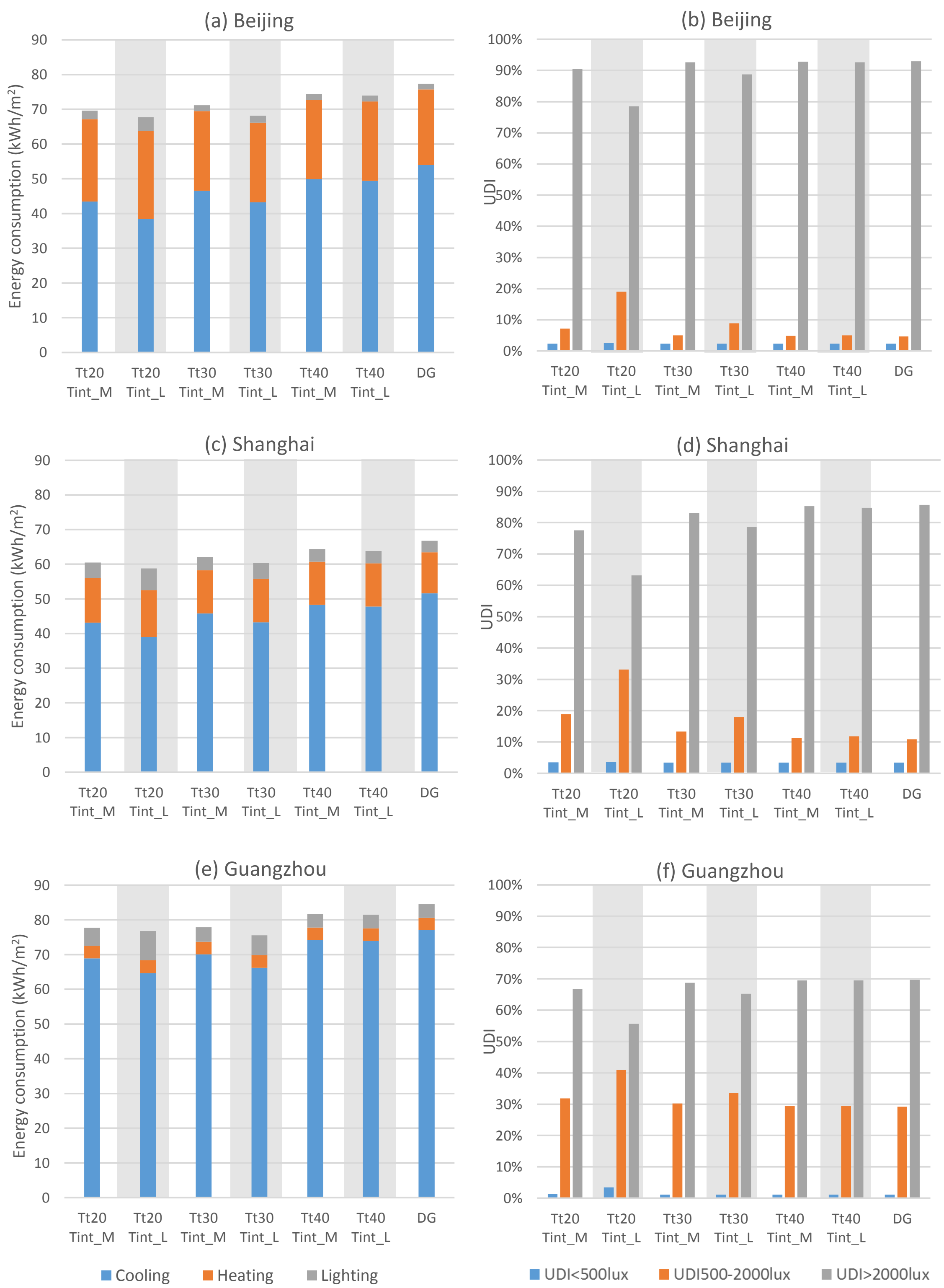


Figure 4.6: Energy consumption and annual UDI levels at sensor I affected by TC_IL-Ni^{II} TC windows with different transition temperatures and lower visible transmittance at tinted state under three climates

4.3.3. Scenario III

Results in scenario II indicated that the Tint_L cases of VO_2_Nano windows are effective to reduce energy consumption, while the Tint_L cases of TC_IL-Ni^{II} windows are beneficial to adjust daylit conditions. Therefore, a balance between energy and daylighting is potential to be achieved by cooperating these two TC materials in the same double-glazing system. In this scenario, energy consumption and UDI distributions affected by the nine pairs of cooperation cases (see section 4.2.3.3) between the two typical TC materials were predicted through simulation respectively.

Figure 4.7 shows cooperation of TC_IL-Ni^{II} and VO_2_Nano with the same transition temperature of 20°C (Same Tt20), 30°C (Same Tt30) and 40°C (Same Tt40). Results show that when transition temperatures of both TC windows are 30°C, cooperation can lead to the most significant energy saving in Beijing. When compared with DG, the energy saving is 14.57%. However, the most optimal cooperation case is the Same Tt40 in Shanghai, reaching maximum energy reduction of 13.50% as compared with DG. It can be seen that, under the climatic conditions of Beijing and Shanghai, a lower transition temperature could result in more heating demand, which would counter the reduction of total energy consumption caused by cooling decrease. However, in Guangzhou, only a little fraction of the overall energy consumption is caused by heating. The increase of lighting demand counterbalances the reduction of cooling demand, resulting in similar overall energy consumption for Same_Tt20, Same_Tt30 and Same_Tt40. It reveals that visible and NIR transmittance decreasing simultaneously during TC transition having a positive effect on energy saving. Figure 4.7 (b) (d) (f) show that, in Beijing and Shanghai, Same Tt 20 leads to the highest percentage of working hours falling in $UDI_{500\text{-}2000lux}$ at sensor I, which is 48.12% and 63.49%, respectively. While in Guangzhou, the highest $UDI_{500\text{-}2000lux}$ is 64.58% caused by Same Tt 30. Different from Beijing and Shanghai, in

Guangzhou, the case with a transition temperature of 20°C has a sharp increase of undersupplied $UDI_{<0\text{-}500lux}$, which countered the increase of $UDI_{500\text{-}2000lux}$ with decreasing transition temperature. That is the reason why the Same Tt30 has higher $UDI_{500\text{-}2000lux}$ levels than the Same Tt20 in Guangzhou.

'VIS_20 NIR_30', 'VIS_20 NIR_40', and 'VIS_30 NIR_40' present the cases when the TC_IL-Ni^{II} cases have a lower transition temperature than the VO_2_Nano cases, which means that visible transmittance into the room adjusted more frequently than NIR transmittance. In Figure 4.7(a)(c)(e), it shows that, when compared with DG, the cases of 'VIS_30 NIR_40' induce more energy saving, but less improvement of $UDI_{500\text{-}2000lux}$, than the other two cases in Beijing and Shanghai. However, in Guangzhou, 'VIS_20 NIR_30' lead to most energy saving (13.68% energy reduction compared with DG), and highest value of $UDI_{500\text{-}2000lux}$ among the three cases.

'NIR_20 VIS_30', 'NIR_20 VIS_40', and 'NIR_30 VIS_40' present the cases when the VO_2_Nano cases have a lower transition temperature than that of TC_IL-Ni^{II}, which means that NIR solar radiation transmitted into the room got the adjustment more frequently than that within the visible spectrum. Results present that 'NIR_30 VIS_40' is the most energy efficient case under the climate of Beijing and Shanghai, and energy saving compared with DG is 17.5% and 15.55% respectively. They are also the most energy reduction achieved among all cases in this scenario. However, their improvement of $UDI_{500\text{-}2000lux}$ at sensor I is restricted. While under the climatic condition of Guangzhou, 'NIR_20 VIS_30' has the most energy reduction by 17.95%, meanwhile, its percentage of working hours within illuminance 500-2000lux range is approaching 67%, which is higher than any other cases of this scenario.

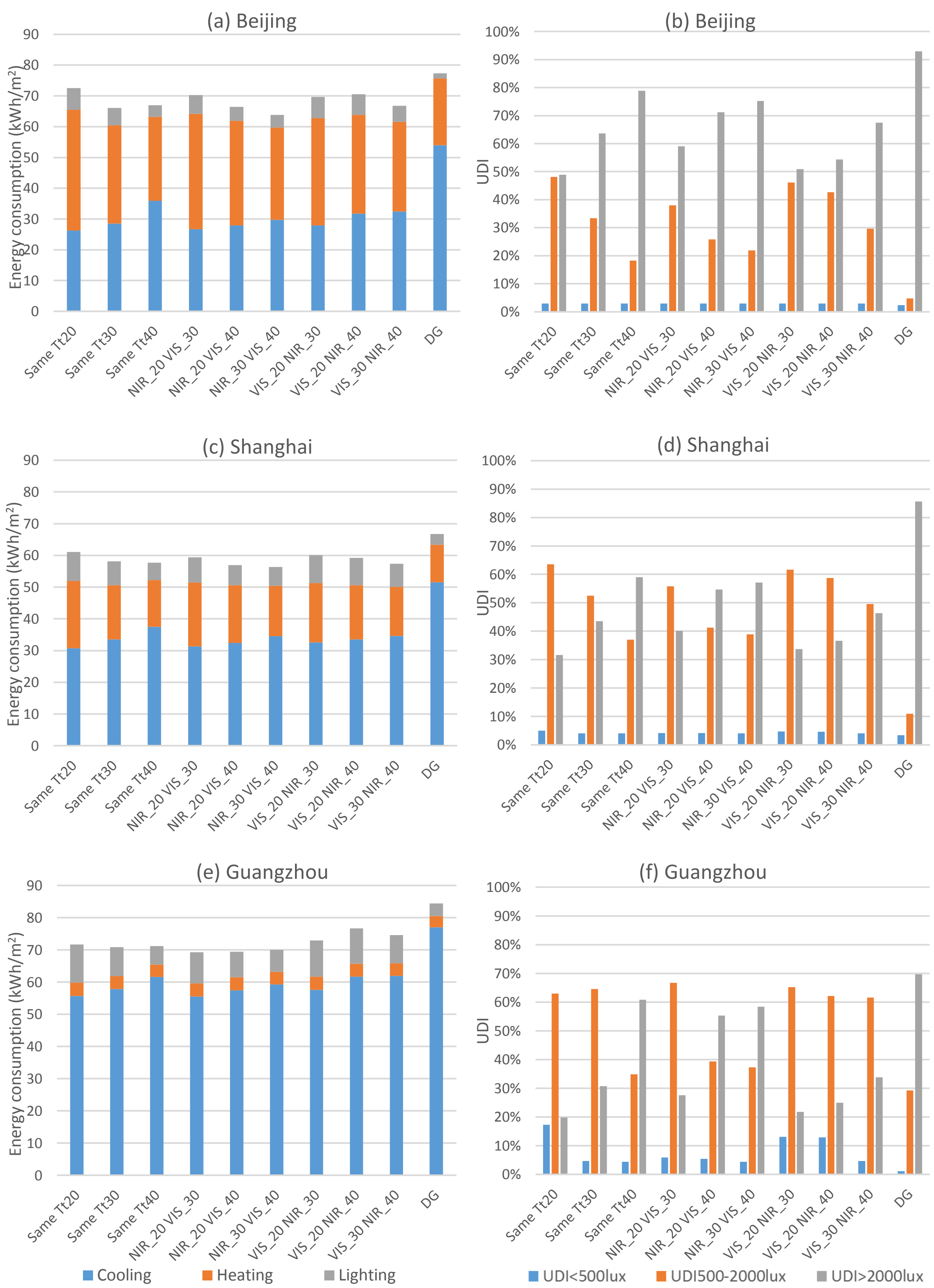


Figure 4.7. Energy consumption and annual UDI levels at sensor I affected by TC windows of scenario III with different transition temperatures and lower visible transmittance at tinted state under three climates.

Under all three climates, the cases of TC_IL-Ni^{II} with a lower transition temperature than VO_2_Nano result in more energy consumption than its corresponding cases that

VO_2_Nano has a lower transition temperature. It is because that decrease of visible transmittance has less contribution to reducing cooling demand, but can cause higher lighting requirement at the same times. In addition, cooling demand accounts for a larger fraction of the overall energy consumption when compared with lighting demand. Additionally, reduction of the visible lighting transmitted is effective to reduce oversupply illuminance more than 2000lux and increase working hours within $UDI_{500\text{-}2000lux}$ bins.

4.3.4. Discussion about weather conditions and TC performance

Table 4.3 reports the energy saving percentages compared with DG affected by the improved VO_2_Nano and TC_IL-Ni^{II} windows described in scenario II (Tint_L cases of VO_2_Nano or TC_IL-Ni^{II} working on their own) and III (Tint_L cases of VO_2_Nano and TC_IL-Ni^{II} working together). It can be seen that some cooperation cases of the two TC materials have not been more energy efficient than using one of them individually. Meanwhile, all pairs of cooperation could lead to more working hours falling into the desired illuminance range 500-2000lux, and the improvement of $UDI_{500\text{-}2000lux}$ compared with DG are rising with the decrease of transition temperatures.

Table 4.3: Summary of energy saving and improvement of $UDI_{500\text{-}2000lux}$ at sensor I affected by the improved TC windows within scenario II and III

Beijing $UDI_{500\text{-}2000lux}$

VO_2_Nano \ TC_IL-Ni^{II}		Tt20	Tt30	Tt40
		14.33%	4.15%	0.30%
Tt20	14.87%	**43.43%****	33.30%**	21.15%**
Tt30	11.41%	41.45%**	28.71%**	17.19%**
Tt40	8.99%	37.94%**	**24.95%****	13.54%**

Beijing Energy Conservation

VO_2_Nano \ TC_IL-Ni^{II}		Tt20	Tt30	Tt40
		12.46%	11.81%	4.41%
Tt20	13.31%	6.24%	9.12%	14.06%**
Tt30	16.93%	9.96%	14.57%*	17.50%**
Tt40	11.16%	8.82%	**13.62%****	13.44%**

Shanghai $UDI_{500\text{-}2000lux}$

VO_2_Nano \ TC_IL-Ni^{II}		Tt20	Tt30	Tt40
		22.23%	7.07%	0.89%
Tt20	27.42%	**52.57%****	44.86%**	30.29%**
Tt30	25.40%	50.69%**	41.55%**	27.96%**
Tt40	23.76%	47.78%**	**38.69%****	26.04%**

Shanghai Energy Conservation

VO_2_Nano \ TC_IL-Ni^{II}		Tt20	Tt30	Tt40
		11.97%	9.51%	4.39%
Tt20	17.05%	8.48%	11.01%*	14.61%*
Tt30	17.62%	9.96%	12.90%*	15.55%*
Tt40	10.90%	11.27%*	**14.06%****	13.50%**

Guangzhou $UDI_{500\text{-}2000lux}$

VO_2_Nano \ TC_IL-Ni^{II}		Tt20	Tt30	Tt40
		11.71%	4.45%	0.20%
Tt20	6.77%	33.79%**	**37.45%****	10.13%**
Tt30	4.64%	35.97%**	35.38%**	8.05%**
Tt40	3.26%	32.95%**	32.31%**	5.63%**

Guangzhou Energy Conservation

VO_2_Nano \ TC_IL-Ni^{II}		Tt20	Tt30	Tt40
		9.14%	10.59%	3.53%
Tt20	15.98%	15.10%*	**17.95%****	17.80%**
Tt30	14.59%	13.68%*	16.13%**	17.12%**
Tt40	12.63%	9.20%*	11.67%*	15.74%**

* Better performance than VO_2_Nano or TC_IL-Ni^{II},
** Better performance than VO_2_Nano and TC_IL-Ni^{II}

4.3.4.1. Cooperation in Beijing

Table 4.3 shows that, under the climatic conditions of Beijing, the cooperation between the TC_IL-Ni^{II} cases with a transition temperature of 40°C and the VO_2_Nano cases with a transition temperature of 20°C, 30°C, and 40°C all have improved performance of energy saving and $UDI_{500\text{-}2000lux}$ increase. Meanwhile, their cooperation performs better than applying each of them individually. The increase of energy conservation compared with corresponding VO_2_Nano windows working on their own is 0.75%, 0.57%, and 2.28%. For $UDI_{500\text{-}2000lux}$, the increase is 6.28%, 5.78%, and 4.55%.

Additionally, combining the TC_IL-Ni^{II} cases with a transition temperature of 30°C and the VO_2_Nano cases with a transition temperature of 40°C leads to higher energy conservation of 2.46%, and a higher percentage of $UDI_{500\text{-}2000lux}$ of 15.96% than that of VO_2_Nano with a transition temperature of 40°C. It means that it is more effective to have the reduction of visible transmittance at a lower temperature than the decrease of NIR transmittance.

The climatic characteristics of Beijing can aid interpreting these results. As Table 4.4 reports, Beijing has the most hours (866 hrs.) falling into the solar incident angle across 20 - 30°, and meanwhile, it has the most accumulated incident solar radiation, where direct daylight accounts for 60%. The most frequent outdoor temperatures are within the range from 0 to 10°C. It means that even if a large amount of solar radiation is available to enter the building, the outdoor temperature is still low, i.e. winter days, early morning or late afternoon. Therefore, the main issue to address during these this period is reducing oversupplied daylighting rather than solar heat gains. That explains why the cooperation of VO_2_Nano T_t40 and TC_IL-Ni^{II} T_t30 could achieve a balance between energy and daylighting improvement.

4.3.4.2. Cooperation in Shanghai

In Shanghai, Table 4.3 presents 2 out of 9 cooperation cases have better energy and daylighting performance than using the TC_IL-Ni^{II} and VO_2_Nano windows on their own respectively. The paired cooperation between TC_IL-Ni^{II} Tt40 and VO_2_Nano Tt40 cases results in 13.50% of energy conservation, and 26.04% increase of $UDI_{500\text{-}2000lux}$, compared with DG. While the TC_IL-Ni^{II} T_t40 case working with the VO_2_Nano T_t30 case results in energy saving of 14.06%, and a $UDI_{500\text{-}2000lux}$ increase of 38.69%, which are more efficient than the former pair. It means that the cooperation of VO_2_Nano T_t40 and TC_IL-Ni^{II} T_t30 is also the most energy and daylighting efficient case for climate of Shanghai. Moreover, VO_2_Nano with a transition temperature of 20°C or 30°C are more energy efficient (i.e., approx. 17%) than any cooperation or individual TC_IL-Ni^{II} cases, and meanwhile, the increase of $UDI_{500-2000lux}$ is around 27%, which is higher than in Beijing and Guangzhou. It is indicated that the current proposed optical properties of VO_2_Nano (i.e., Tint_L, Tt of 20°C or 30°C) are suitable for climates in Shanghai.

As described in Table 4.4, Shanghai has the most hours falling into solar incident angle ranging from 30° to 40°, where direct solar radiation accounts for 50% of total amount, the outdoor temperature is mostly falling into the range across 10-20°C. Compared to Beijing, Shanghai has higher solar incident angles and temperatures, but less solar radiation is arriving on the window surface. It means that compared with adjusting visible daylighting, solar heat gains are more desired to be controlled. That explained the more energy efficiency of VO_2_Nano with a lower transition temperature.

4.3.4.3. Cooperation in Guangzhou

Results in Table 4.3 show that 5 out of 9 paired cooperation cases are detected to be significant for both energy and daylighting improvement. The TC_IL-Ni^{II} Tt40 case combining with the VO_2_Nano Tt20, Tt30, and Tt40 cases, respectively, all had better energy performance than each of them working on their own. The increase in energy saving compared with the corresponding VO_2_Nano window is 1.82%, 2.53%, and 3.11%, respectively. However, the increase percentage of working hours within desired $UDI_{500-2000lux}$ is limited, up to 3.41%. The TC_IL-Ni^{II} Tt30 case cooperating with the VO_2_Nano Tt20 and Tt30 cases, respectively, also result in more energy saving than using each of them individually, and the increase is up to 1.97%. Meanwhile, the working hours within $UDI_{500-2000lux}$ increase significantly by 30%. The results reveal that, in

Guangzhou, reducing NIR transmittance at a temperature lower than that of reducing visible transmittance is more effective to achieve both energy saving and desired daylight availability. Additionally, due to most of the paired cooperation result in more energy saving, further reduction of NIR transmittance is likely to be required.

Under the climatic conditions of Guangzhou, the most frequent solar incident angle is ranging across 40-50°, where the accumulated incident solar radiation is reported to be lower than that of Beijing and Shanghai. Meanwhile, the direct solar radiation occupies 45% of the total. It can be seen that within all solar incident angle ranges, 20-30°C is the outdoor temperature range that the most hours are falling in. It means that Guangzhou mainly has high temperatures, but less solar radiation arriving onto the building surface. Therefore, in Guangzhou, reducing solar heat gains by blocking NIR solar radiation is the most significant way to reduce the significant cooling energy consumption. That explains the improved energy and daylight performance caused by cooperating with VO_2_Nano with lower transition temperature.

Table 4.4: Climatic conditions of the three cities, including solar incident angles, incident/diffuse solar radiation [102]

Solar Incident Angle (degree)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90
Beijing									
Frequency (hours)	692	759	886	670	534	433	329	101	0
Accumulated incident solar radiation (W/m^2)	20139	106827	287084	229958	175171	149311	106780	30336	0
Accumulated direct incident solar radiation (W/m^2)	5723	50830	173270	132266	86920	70100	44782	11250	0
Accumulated diffuse incident solar radiation (W/m^2)	12209	46195	89603	72256	62861	54267	41520	12685	0
Temperature (°C) (Hours)	20-30 (198)	0-10 (236)	0-10 (357)	20-30 (218)	20-30 (267)	20-30 (275)	20-30 (244)	20-30 (62)	0
Shanghai									
Frequency (hours)	628	616	671	804	587	481	334	249	30
Accumulated incident solar radiation (W/m^2)	11120	46925	112719	218720	142976	113847	82547	56688	5497
Accumulated direct incident solar radiation (W/m^2)	1931	14556	47310	108594	57120	36896	25437	13799	709
Accumulated diffuse incident solar radiation (W/m^2)	7624	26322	51564	84945	63793	55076	39386	28910	3423
Temperature (°C) (Hours)	20-30 (207)	20-30 (205)	10-20 (218)	10-20 (291)	20-30 (247)	20-30 (251)	20-30 (152)	20-30 (140)	20-30 (27)
Guangzhou									
Frequency (hours)	564	566	558	663	757	466	377	327	108
Accumulated incident solar radiation (W/m^2)	8743	38293	72391	124066	188066	95943	63390	57866	18614
Accumulated direct incident solar radiation (W/m^2)	1559	12843	30089	54093	84716	31427	10042	5385	535
Accumulated diffuse incident solar radiation (W/m^2)	5936	20628	33128	52881	77042	47414	39917	38446	13331
Temperature (°C) (Hours)	20-30 (331)	20-30 (310)	20-30 (306)	20-30 (376)	20-30 (386)	20-30 (289)	20-30 (185)	20-30 (164)	20-30 (58)

4.4. Summary

This chapter carried out a series of scenarios to explore the potential development of TC materials by varying transition temperature, visible and NIR transmittance, and TC material cooperation to reduce oversupplied daylighting and improve energy conservation. The findings were summaried as:

1) Both selected TCs have their proper transition temperatures depending on different climates, which are higher than room temperature around 30-35°C for VO_2_Nano windows. While TC_IL-Ni^{II} windows required a transition temperature of 20°C or less, to achieve the most significant energy saving.

2) Both TCs are effective to reduce the oversupplied daylighting in the region near the window, however, because of the original high visible transmittance (i.e., 0.97-0.79) of the TC_IL-Ni^{II} film, resulting in the restricted capacity of adjustment within visible spectrum.

3) Increasing the reduction of NIR transmittance for VO_2_Nano, and visible transmittance for TC_IL-Ni^{II} improve the energy efficiency compared with original configurations. Meanwhile, the optimal transition temperatures of improved VO_2_Nano and TC_IL-Ni^{II} windows are not affected in Beijing and Shanghai. However, in Guangzhou, the optimal transition temperature of VO_2_Nano decreased with larger NIR spectral reduction, while that of TC_IL-Ni^{II} increased with larger visible spectral reduction.

4) Improved TC_IL-Ni^{II} window has better performance in terms of daylighting adjustment, but still less effective compared to the VO_2_Nano windows, it is because of its high visible transmittance at clear state.

5) Cooperation of TC_IL-Ni^{II} and VO_2_Nano films led to further improvement of both energy and daylighting performance, and cooperation methods depend on climatic characteristics:

In Beijing, 'VIS_30 NIR_40' is the best case, i.e., reducing the oversupplied daylighting on cold days, and both overlit and overheat on hot days;

In Guangzhou, 'NIR_40 VIS_30' is the best case, i.e., reducing the oversupplied daylighting and overheat during hot days, and keeps sufficient daylighting on warm days;

In Shanghai, both improved VO_2_Nano working alone and 'VIS_30 NIR_40' are good, because of its moderate warm climates.

Chapter 5

Human Response to Tinted TC Windows

5.1. Introduction

Humans spend most of their time inside buildings. In fact, during the day, it is estimated that some individuals spend approximately 90% of the time inside offices [17, 129]. In building standards, designers aim to deliver task lighting for the visual needs of the occupants [130]. This is to provide clarity of the task and reduce visual stress, eye fatigue and headaches [106, 130-132]. Therefore, illuminating the indoor environment has become an important attribute in the workplace, which plays a significant role in occupant performance [17].

In office buildings, illumination of the visual environment usually requires a balance between daylight and artificial light. However, most studies often indicated that office workers often prefer workspaces illuminated by daylight [133]. Other than stimulating the visual system, daylight also has a significant influence on non-visual responses [133-138]. It helps regulate the human circadian rhythm and internal biological processes, which have a large role in maintaining the health and well-being of building occupants [139-141].

In recent decades, however, the luminous conditions of office buildings are often dependent on large area fenestration systems containing various window technologies (i.e., low-e coating, insulated glazing, chromogenic glazing, louvres, and blinds, etc.) [7, 114, 120, 121].

In the literature, previous human performance studies using different types of tinted windows have provided restricted conclusions. Pineault *et al.* [142] conducted a study on the effect of coated and tinted windows on daylight quality. Tinted glazing showed to be effective in reducing glare, however, also creating a space more artificial and less pleasant. Arsenault *et al.* [17] compared subjective assessments of three types of glazing (i.e., blue, clear and bronze) and found that observers showed a preference towards the daylight that was transmitted through a bronze window, while a blue glazed window was linked to reducing arousal levels.

Innovative glazing containing different colours has also been studied. Blue tinted electrochromic windows were accepted by occupants and also reduced glare [143]. A window with 25% covered with red luminescent solar concentrating glazing obtained more positive responses on visual comfort than a normal clear window [18]. However, in the last decades, studies on visual responses to different indoor chromatic (coloured) environments were mostly carried out in conditions lit by artificial sources. Luminances and correlated colour temperatures (CCT) were mainly considered as the parameters that most influenced visual perception.

Harrington [144] showed that the apparent brightness improved by 1% by per 100 K increase in CCT. A study by Fotios and Livermore [145] indicated that, even in low illuminance conditions, observers showed a preference towards lamps containing a higher colour rendering index and CCT. Boyce [146, 147] found that pleasantness, colourfulness, visual distinctness and satisfaction all improved with the increasing levels of illuminance, colour rendering index and CCT. In addition, across CCT ranges between 2700-6300 K, changes in illuminance were given more effective responses (i.e., sensitive to the change of illuminance levels, and bright environment increases pleasantness) than variation in CCT [148, 149].

In addition to visual responses, blue-enriched and high CCT (~17000K) has shown to be able to improve the alertness [150-152]. However, most of the studies indicated that warm CCTs around 4000K were more acceptable in terms of visual preferences [21, 153]. In a four-month experiment, using an open office lit by artificial lighting with partial daylight access, study [21] findings showed that 3500 K was more comfortable when compared with 5000K luminaires, which was perceived too cool and bright for using computer screen at high luminance.

Creveld [154] and Odabasioglu [155] explored the roles of visual clarity and comfort, brightness and preference with various coloured light. This showed that red and blue light provides relative brighter luminous conditions, but blue light reduced the visual clarity of Snellen chart tests. On the other hand, white and green lights were considered to be more comfortable by observers. In addition, studies have shown that coloured indoor decoration can also influence the visual perception when considering the CCT of the indoor environment [156].

Thermochromic (TC) windows are considered as one of the most promising building components, which can be used to regulate – dynamically and automatically – the indoor thermal and luminous conditions and achieving potential energy savings [12, 15, 99]. However, previous studies in building applications mainly focused on the thermochromic material development and energy performance [8, 13, 16]. Additionally, a limited number of studies have explored the effect of TC windows on daylighting distribution and uniformity [15, 16].

In studies focusing on TC window development, the influence of the window colour (i.e., brown, blue, etc.) on responses given to the visual scene from the building occupant are rarely considered. In rooms containing TC windows, daylight – transmitted into space through the window's optical properties – would be one of the main sources of illumination. Therefore, different colours used in the TC windows will also result in different colour appearances within the indoor visual scene.

In summary, the change of CCT due to the TC glazing might impact on both the visual perception of the indoor environment as well as the personal psychologically sensations of the occupants. In this study, an innovative test room cubicle lit by an artificial window was designed to investigate whether the visual responses given by test participants are influenced by different TC glazing containing different colours. Especially, the study aims to investigate visual responses when carrying out both objective tasks (i.e., achromatic acuity, chromatic acuity and colour discrimination) and subjective assessment under different coloured TC windows.

5.2. Methodologies of assessing chromatic glazing and visual perception

To investigate the effects of chromatic glazing, the visual response has commonly been evaluated under two types of luminous environments: daylit and artificial lighting.

5.2.1. Experiments under Daylit Conditions

Daylight emitted from the sun as electromagnetic radiation has a continuous spectrum power distribution at all parts of the visible wavelength range. However, depending on meteorological conditions (i.e., time of the day, latitude, weather, etc.) daylight transmitted into the building changes frequently over the time. Since it is easier to change the window types frequently, most studies have used small-scale models to simulate the visual scene and investigate the visual perception of different glazing types. Instead of performing experimental tasks in full-scale test rooms, observers were required to look into scaled models, whereby the experimental conditions were maintained inside. In these studies, subjective assessments were used to evaluate the observer's reaction to, for example, brightness, naturality, shadows, beauty, and pleasantness.

Typically, small-scale models have been used to assist in the design of the fenestration investigate daylight distribution patterns. Bodart [157] states that scale choice should be depended upon different design considerations, in particular, when studying the accuracy of diffuse and direct daylight conditions. When to considering measurement devices and user assessment, the most suitable scales should be between the ranges of 1/10 to 1/1 [157]. Additionally, the photometric distribution of small-scale model was proved to be more similar to full-scale model in cloudy (diffused) sky conditions [158, 159].

Dubois and Cantin [160] used 1:7.5 scale model investigates the visual responses under the effect of six coated glazing materials. Especially, they studied the relationship between the interior conditions and the view to the outdoor environment using subjective assessments about naturalness, colour temperature, pleasantness, visual comfort, shadow, etc. Additional studies by the same authors were used in two tests containing 1:6 scale models implementing the same methods and obtained the same results as the initial study, i.e., higher transmittance glazing led to more positive ratings for naturalness, pleasantness, and sharpness [161]. Arsenault *et al.* [17] and Vossen *et al.* [18] also conducted their experiments about chromatic windows using 1:4 and 1:6 scaled model respectively.

Experiments under daylight conditions have the advantages of restoring the daylight distribution inside a practical building. However, the variation of the daylight is uncontrollable, which means that a large number of sample is required and the difficulties of data analysis are increased. Additionally, subjective assessments by looking into the scaled model instead of being in the experimental conditions might restrict the perception of subjects, e.g. the sight position is quite different from that in practical.

5.2.2. Experiments under Artificial Lit Conditions

In different studies, several test procedures have been commonly used to examine the effect of lamp spectrum on apparent brightness in controlled artificial test room conditions [19, 162]. The side-by-side brightness matching procedure uses two adjacent identical interior visual scenes. The observer is required to adjust the luminance of one scene until the two interiors are (as near as possible) meet the prescribed visual criteria [144-146, 163]. Brightness ranking procedure, this technique sequentially presents two sources of fixed illuminance. The observer is then instructed to identify which of the conditions appeared brighter [144, 164]. The category rating procedure, typically, uses semantic differential rating scales, whereby the observer is required to rate the brightness of an interior space on a seven-point scale from dim to bright [147].

Studies by Creveld, Manave, and Wei [21, 148, 154] examined visual responses when focusing on illuminance, CCT, and the relationship between both. Common factors that may influence the observer's responses to the visual scene fall into two broad categories: objective tasks and subjective assessment.

Table 5.1 presents the main factors that have been explored in the previous studies. To evaluate visual performance, objective measurements that have been recorded include accuracy (freedom from errors), the rate of performance (speed), and reaction time in conditions where subjects are carrying the tests under different lighting conditions.

For example, in a study by Fotios [165], 30 participants were instructed to perform tasks lit by different types of commonly used street lamps with different spectral power distribution (SPD). 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. Results were obtained by comparing the numbers of correctly read across different lighting conditions.

Table 5.1: 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	To investigate the influence of treatment conditions on the clarity of vision	[20, 154, 165, 166]
Contrast	Pelli-Robson Contrast Sensitivity chart	The contrast of the target quantifies its relative difference in luminance form the background	[167, 168]
Colour naming	Gretag Macbeth colour checker chart; 24 colour samples: semantic rating	Explore the different lighting conditions that would influence colour discrimination	[169, 170]
Test reading, writing/ typing	Letter searching Typing/writing	Test the if different lighting conditions would influence the concentration	[166, 168]
Subjective assessments			
Arousal	Subjective scales: Likert scale Bipolar scale Visual analogue scales (VAS)	Test the degree of alertness caused by different lighting conditions	[17, 148, 154, 155, 160, 161, 166, 171-174]
Light level		The perception of brightness	
Colour temperature		The perception of cool or warm light	
Naturalness		Test whether visual conditions create conditions that would appear artificial	
Pleasantness		Whether certain lighting conditions change the mood of an observer	
Comfort		Whether the visual conditions produce feels of discomfort (i.e., glare)	
Sharpness		Whether lighting conditions create visual targets that are blurred	
Shadows		Describe characteristics of shadows (i.e., blur or sharp, soft or hard)	
Spaciousness		Describes 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.* [174] collected information of, respectively, visual comfort, alertness, and mood under different of daylit and artificial lit conditions. While in a test room, the participants were required to evaluate various conditions using visual analogue scales (VAS).

Unlike daylit conditions, artificial lighting conditions offer a larger degree of control over the luminous conditions (i.e., illuminance and CCT). This allows the researcher to easily vary the visual conditions and also test a wide range of experimental variables.

Therefore, this study aims to test the influence of different chromatic glazing types on the visual performance of participants in controlled artificial conditions.

5.3. Methodology

To investigate the visual responses in a working environment lit by glazing with different thermochromic films studied in Chapter 4, an experiment was designed under controlled laboratory conditions.

Based on the design considerations of an artificial window [175], an array of lighting emitting diodes (LEDs) was used to simulate the daylight coming from outside to a window. Different thermochromic films could then be applied onto the window, which was used to create the luminous conditions inside a small test room simulating an office cell. For this experiment, 31 participants 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.

5.3.1. Experimental setup

5.3.1.1. Test room cubicle and an artificial window

For this study, a controlled setting allowed the use different coloured films containing similar photometric properties of thermochromic glazing to be closely studied under artificial lighting conditions.

Figure 5.1 shows the test room cubicle placed inside a laboratory space inside the Energy Technologies Building (ETB) located at the University of Nottingham. This cubicle was made of wooden partitions with dimensions of 1.5 m (length) ×1.2 m (width) × 2.1 m (height). The spatial dimensions were based on the recommendations made by the workplace health and safety standard (i.e., the minimum space for per person should be not less than 11 cubic meters (11 m^3) with ceiling height no more than 3 m) [176]. Previous studies indicated that, a model scaling ranging across 1:1 - 1:10 would be suitable when performing subjective assessments. Therefore, size of this test room cubicle (i.e., 3.78 m^3, approximately 1:3 comparing to the minimum 11m^3) meets this requirement [157], which means that the experimental space size is easily accessible for test participants. To evenly diffuse the lighting inside the test room, the interior surfaces were painted matte-white [177].

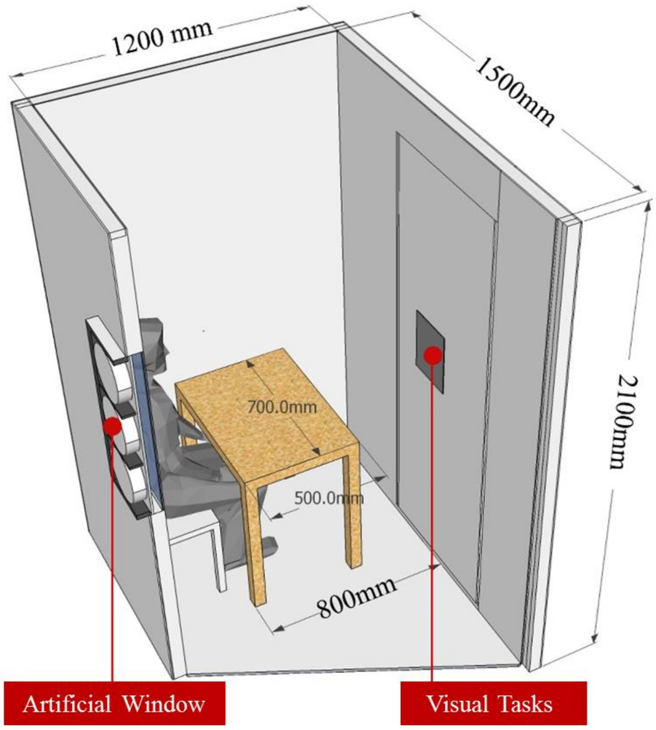


Figure 5.1: Schematic of the test room cubicle with test participant positioned inside

At a distance of 0.9 m from the floor, an opening of dimension 0.54 m × 0.72 m was placed in one of the walls. Figure 5.2 shows actual photographic images of the integrated artificial window components seen from outside of the test room cubicle and a section illustration of the various layers used. In the opening created inside the wall, an artificial window consisting of 6 LEDs was installed. On the opposite wall, directly across from the artificial window, visual tasks could be mounted on the nearby wall surface, and the distance between the artificial window and the visual tasks is 1.2 m. Based on the design considerations of Mangkuto *et al.* [175], the artificial window consisted of a light source, light filter and front cover glazing.

(a) view inside test room (b) view outside test room (c) Section of artificial window

Figure 5.2: The configuration of the designed artificial window

A total of 6 Lightwell 18 W energy-efficient Frosted Ceiling lights LEDs were mounted to form a compact array. Since the spectral irradiance of the LEDs selected was approximate to natural daylight, this also made 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 6 integrated LEDs 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 were used to filter light and create diffused light 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).

The light spectrum of integrated artificial window system (i.e., red curve in Figure 5.3), which was measured by Ocean Optics Spectrometer USB2000+UV-VIS, was noted to have a similar shape with that of daylight under AM1.5 (i.e., the grey curve in Figure 5.3).

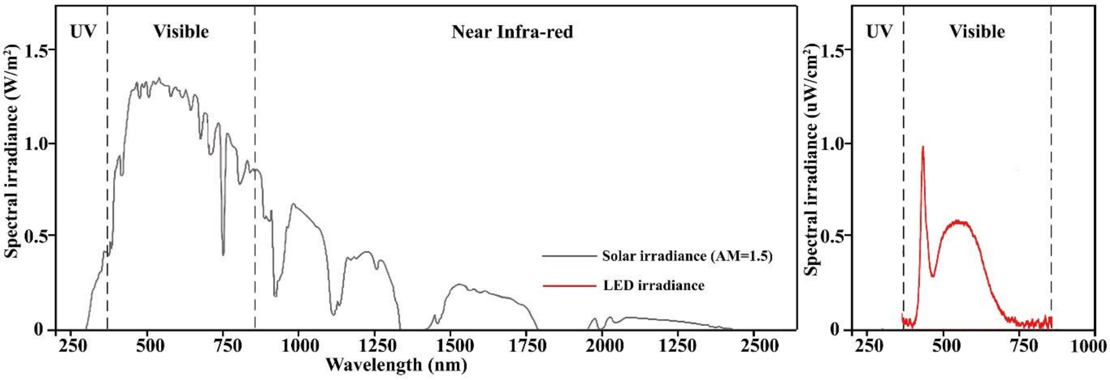


Figure 5.3: Solar spectral irradiance (left) and lighting spectrum through clear acrylic glazing (right)

5.3.1.2. Thermochromic window films

According to the literature, there are two types of thermochromic materials in terms of their colours. Type 1) is the vanadium oxide (VO_2) -based thermochromic films, which has slight changes occur in the visible spectrum (e.g., 380-780 nm) and larger changes occur near infrared spectrum (e.g., >780 nm) [10, 13]. Especially, VO_2 nanoparticle (i.e., VO_2_Nano) films are capable of changing the transmittance of incident radiation based on it spectral properties at the temperature rising above approximately 60°C by tinting the film giving it a bronze visual appearance [34]. Type 2) is a series of composite films of ionic-liquid-nickel-complex-polymer The films have properties that allow it to change the visible transmittance. Especially, the film containing $[bmim]_2\ NiCl_4$ (i.e., TC_IL-Ni^{II}) has visible transmittance reducing with temperature increasing from 25 to 75°C. At 25°C, the films have a clear appearance, but the properties of the materials will allow the film to be tinted giving it a blue visual appearance at 75°C [8, 9].

In this study, the films with similar photometric properties found in Type 1 and Type 2 films were used to investigate visual responses within the test room cubicle. To investigate the visual responses given to the two types of thermochromic materials, two samples of bronze and blue films were selected to be used in this experiment.

In Figure 5.4 (a) and (b), visible spectral transmittance measurements of the two selected thermochromic materials. The blue lines represent the visible spectral transmittance performance of the actual TC glazed material under their tinted state, while the red lines represent the spectral transmittance of the materials films when applied in the test room cubicle. When measuring the spectral transmittance values of these sample films using a calibrated Ocean Optics Spectrometer USB2000+UV-VIS, it can be seen that the photometric properties closely match those found in most tinted states of actual VO_2_Nano and TC_IL-Ni^{II} products, respectively (see Figure 5.4).

Figure 5.4 (c) shows a comparison between the light spectrum transmitted through bronze, blue, and clear glazing films. It can be seen that blue film has the highest spectrum across wavelength peaking between approximately 380-500nm (blue), while the bronze film has the highest spectrum peaking between a wavelength of approximately 570-700nm (yellow/red).

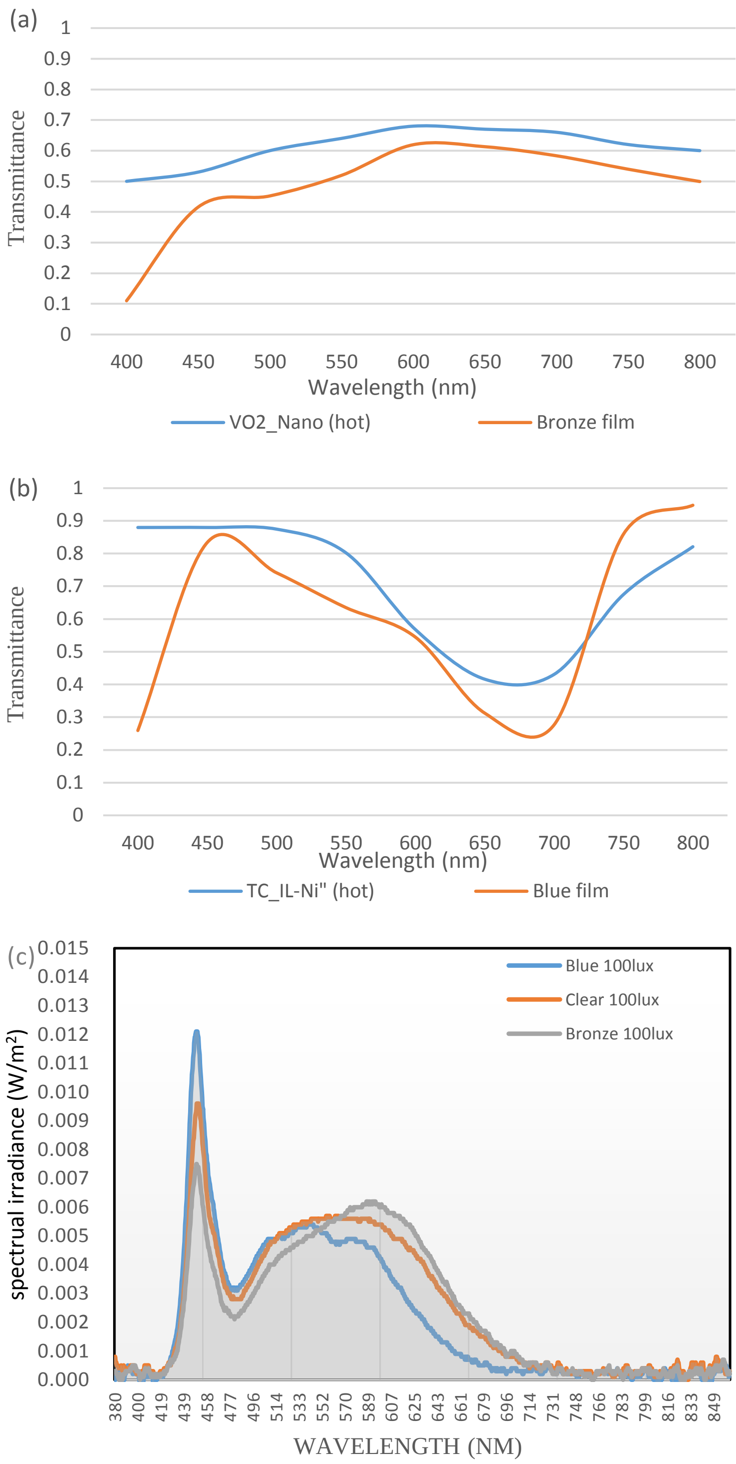


Figure 5.4: Spectral properties of the TC windows at the tinted state and the selected colour films [8, 9]

Figure 5.5 shows photographic images of the view inside the test room cubicle lit by the artificial window as seen through 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 5.5: Photos of lighting environment for the experimental chamber with three different films

5.3.1.3. Photometric Lighting Conditions

Inside the test room cubicle, the parameters known and alleged to influence visual perception, such as illuminance levels, temperature, 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 constent at approximately 25^{o}C, and humidity was in a range between 45%-55%. According to CIBSE guide A, a moderate comfort thermal environment could be met [106].

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 5.2). The human visual system has a limited range of capabilities, and these limits are called thresholds of vision. 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 a working environment [108]. While under this threshold luminance condition, suprathreshold of visual task performance was measured, i.e., the largest magnitude of accuracy.

Table 5.2. Illuminance level in lux and colour temperature in K under different treatment conditions of vertical and horizontal surface

	Vertical surface		Horizontal surface	
	Illuminance (lux)	CCT(K)	Illuminance (lux)	CCT (K)
1.VO_2_Nano window	103	4056	88	3992
2. Clear window	102	4911	89	4848
3. TC_IL-Ni^{II} window	101	7054	85	6932

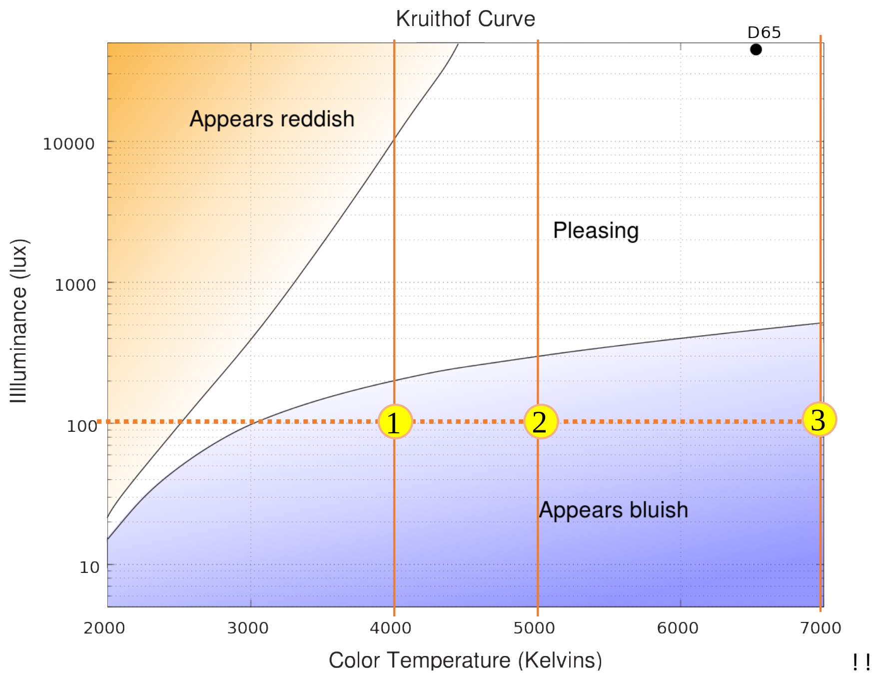


Figure 5.6: Kruithof curves with measured CCT: Point 1= VO_2_Nano; Point 2= Clear, and Point 3= TC_IL-Ni^{II} window condition. (Kruithof curve, modern version, source: https://en.wikipedia.org/wiki/Kruithof_curve, modified by author)

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 chromameter. By changing the films attached to the clear acrylic used to simulate the artificial window, the visual conditions inside the test room cubicle could be easily changed. The main difference across the three conditions can be seen in the measured values of CCT, as is shown in Table 5.2.

During the measurement, the chromameter was placed on the target surfaces and repeated measured to reduce errors. 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.

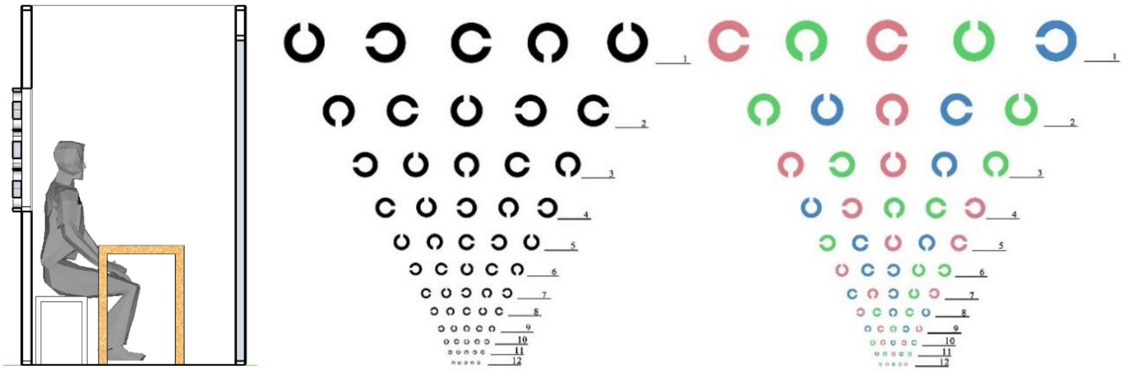
The Kruithof chart was also used to demonstrate the expected visual appearance of the combined illuminance and CCT values as is shown in Figure 5.6. It is noted that, under a fixed illuminance of 100 lux, Kruithof curve reports that observers may feel that the working environment is bluish under all three conditions with CCT ranging from 4000 K to 7000 K [178]. However, under this low brightness (i.e., <300 lux), whether the visual responses of observers will be influenced if different tinted TC windows were applied is not yet known.

5.3.2. Visual tasks

The Landolt ring chart was used to measure visual acuity and colour discrimination of test participants. It is proven that visual test using Landolt rings are repeatable and relatively more accurate [165].

The two charts used in this study are shown in Figure 5.7. 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 participant.

Both achromatic (without colour) and chromatic (with colour) acuity were measured using black (Figure 5.7(b)) and coloured (Figure 5.7(c)) ring charts, respectively. In a repeated task, the colour naming test was also carried out the Landolt ring chart in Figure 5.7(c). To ensure a constant background lumianance, the charts were printed on matte white paper containing similar properties found on the interior surface of the test room. This prevents unwanted contrast effects between the task paper when mounted against the surface walls.



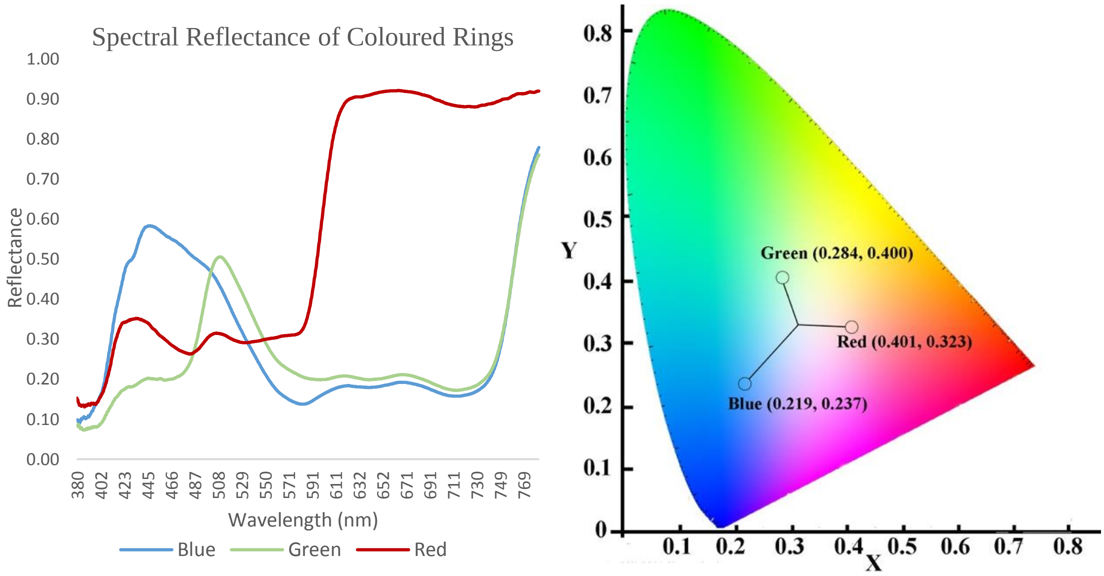
(a) view position of the participant (b) achromatic Landolt rings (c) chromatic Landolt rings

Figure 5.7: Section view of the participant 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 [179, 180]. The largest ring is equivalent to the size of 8.0 M letter (where, M-units specifies the height of typeset materials, 1 M= 1.5 mm), and the smallest one is 0.63 M letter. The gap size ranges from 10.8 min of arc to 0.6 min of arc at the viewing position (where, min of arc is a unit of angular measurement, 1 min of arc = 1/60 degrees).

For the chromatic Landolt ring chart, three colours of rings were used based on the literature [165]: red, blue and green representing the three main components of the RGB colour model. The total number of each coloured rings were identical to the achromatic task, but the direction of gaps found in the rings was 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 5.4). WS-1 Reflectance Standards (Table 5.4) was used to measure the spectral reflectance of each printed colour ring. Figure 5.8 illustrates the measured spectral reflectance of each colour and also their position 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 5.8: Spectral reflectance and Chromaticity under standard D65 light source

Under the three different window conditions (clear, bronze and blue), the luminance contrasts of achromatic and chromatic chart were measured (Table 5.3) using a Minolta LS-150 luminance meter (Table 5.4). 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 to the Equation [1]:

$$C = \frac{L_t - L_b}{L_b} \qquad \text{Equation [5.1]}$$

Where, background luminance (cd/m^2) is the immediate surroundings of the Landolt rings on the chart paper, and target luminance (cd/m^2) is the luminance measured on the rings.

Table 5.3: Background and targets (black, green, red and blue rings) luminance, as well as corresponding calculated contrast.

		Clear		TC_IL-Ni^{II}		VO_2_Nano	
		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 5.4: 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	[181]
Ocean Optics	Halogen Light source HL-2000	0.25% Stability of optical output	Provide lighting	[182]
Ocean Optics	Reflectance Standards WS-1	Reflectivity > 98% for 200-1500nm	Standard reflectance	[183]
Campbell Scientific	Temperature and relative humidity probe CS215	Accuracy ± 0.4 °C for temperature and ± 2% for humidity	Temperature; humidity	[184]
Konica Minolta	Chroma-meter CL-200A	± 2% Accuracy ± 0.2% Repeatability	Correlated colour temperature(K); illuminance (lux)	[185]
Konica Minolta	Luminance meter LS-150	± 2% Accuracy ± 0.2% Repeatability	Luminance (cd/m^2)	[186]

5.3.3. Questionnaires

At the beginning of the study, general demographic information from the participants (i.e., age, gender, visual acuity (i.e., glasses or contacts), ethnic background) were collected (See Appendix A).

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

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. Similarly, 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 corresponds 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 [187].

Table 5.5: 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

In addition, as is shown in Table 5.5, five-point Likert scales using semantic bipolar words were used to obtain subjective assessments of 16 questionnaire items measuring, respectively, light levels, colour appearance, distribution, naturalness, pleasantness, and overall comfort. Based on the literature, most of the factors play a significant role in how the quality of the luminous environment indoors can be described. Therefore, questions focused on detecting the influence of lighting colours.

5.3.4. Experimental procedure

During an initial test using 6 participants, the experimental procedure was piloted to verify its feasibility. The main experiment was then conducted in June 2017. The experimental procedure and questionnaires applied to the study were all assessed and approved by ethics committee from the university.

In the main experiment, a total of 31 volunteers participated in the study. They were recruited in the Energy Technologies Building from the University of Nottingham using online advertisements. Participants were all postgraduate students, between the ages of 20 and 45 years, 24 male and 7 female. None of the participants reported any visual problems (i.e., colour perception) and 16 participants wore corrective lens during the experiment.

In this part of the experiment, participants were taken to the resting area. This was a foyer found within of Energy Technologies Building outside the test room area, where horizontal illuminance is approximately 200 lux at 0.8 m height from the floor. Here, the participant was given a copy of the consent form, the questionnaire featuring demographic information, and an overview of the experimental procedure. If the participant had no further questions following the introduction, they were then taken into the test room inside the cubicle. In the test room cubicle, detailed experimental steps were explained and demonstrated was given to ensure the participant was able to carry out the experimental procedure independently.

During the experiments, participants were required to be seated on a chair located inside the cubicle, with their back straight and their visual gaze positioned at the correct viewing position as shown in Figure 5.7 (a). The participant was remained inside during the test, while the experimenter stayed outside the cubicle and could vocally guide them through the procedure.

Under each window condition (Clear, VO_2_Nano and TC_IL-Ni^{II}), the participant was asked to complete three tasks, a gap detection task for both achromatic and chromatic charts and a colour naming tasks for only the chromatic chart. In the gap detection task, the participant was instructed to vocally indicate where they believe the gaps in each ring were according its cardinal direction (e.g., up, down, left or right). When they could not see the gaps clearly, they were encouraged to guess the answer. The gap detection task was performed for both the achromatic and chromatic charts. For the chromatic Landolt ring chart, an additional colour naming task was also performed. The participant was instructed to vocally indicate the colour of each ring. When they could not clearly recognise the colour of a ring, they were again encouraged to guess the answer.

When the participants seated on the specific position and got 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 completion by saying ‘finish’. Then they were instructed to change the test chart after one test session completed, and start the next session following the same steps.

To avoid unwanted procedure biases (fatigue and learning), the tasks were randomly assigned to participants.

When completing the tasks under one window condition, the participant was required to fill a questionnaire with 16 questions according to their experimental experience. To record the visual performance of the participant, two parameters were measured in each of the tasks, the rate of speed and the accuracy (freedom from errors) [165, 188]. Both parameters were measured using a portal dictaphone that was mounted near the viewing position of the participant inside the cubicle. When changing the window conditions, a 2 minutes period of relaxation was provided to the participant under normal lighting levels in the foyer.

5.4. Statistical analysis

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

In order to simplify and clarify the performance of each test under every window condition, nomenclatures are shown in the following grey rectangle, the short names will be used in the following writing.

Nomenclatures

AA --- Achromatic Acuity **CA** --- Chromatic Acuity **CN** --- Colour Naming

Clear_AA --- Achromatic Acuity under clear window condition

Clear_CA --- Chromatic Acuity under clear window condition

Clear_CN --- Colour Naming under clear window condition

TC_IL-Ni^{II}_AA --- Achromatic Acuity under TC_IL-Ni^{II} window condition

TC_IL-Ni^{II} _CA --- Chromatic Acuity under TC_IL-Ni^{II} window condition

TC_IL-Ni^{II}_CN --- Colour Naming under TC_IL-Ni^{II} window condition

VO_2_Nano_AA --- Achromatic Acuity under VO_2_Nano window condition

VO_2_Nano_CA --- Chromatic Acuity under VO_2_Nano window condition

VO_2_Nano_CN --- Colour Naming under VO_2_Nano window condition

Clear_AAt --- Time spent on Achromatic Acuity under clear window condition

Clear_CAt --- Time spent on Chromatic Acuity under clear window condition

Clear_CNt --- Time spent on Colour Naming under clear window condition

TC_IL-Ni^{II} _AAt --- Time spent on Achromatic Acuity under TC_IL-Ni^{II} window condition

TC_IL-Ni^{II} _CAt --- Time spent on Chromatic Acuity under TC_IL-Ni^{II} window condition

TC_IL-Ni^{II} _CNt --- Time spent on Colour Naming under TC_IL-Ni^{II} window condition

VO_2_Nano_AAt --- Time spent on Achromatic Acuity under VO_2_Nano window condition

VO_2_Nano_CAt --- Time spent on Chromatic Acuity under VO_2_Nano window condition

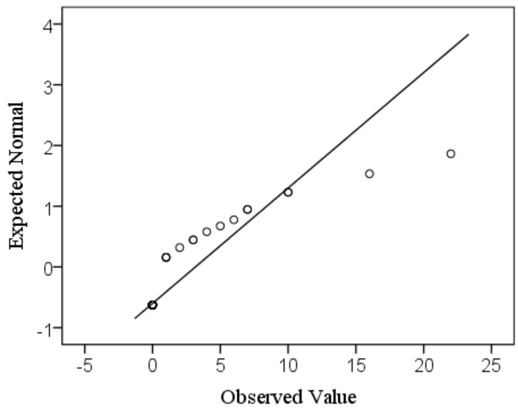
VO_2_Nano_CNt --- Time spent on Colour Naming under VO_2_Nano window condition

SPSS statistics 23 was used to analyse the experimental data in this study. As the main dependent variable in this study (e.g., the measurable outcome), two variables were used to measure the visual performance of the test participants under in each of the conditions. These were the time it took participants 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.

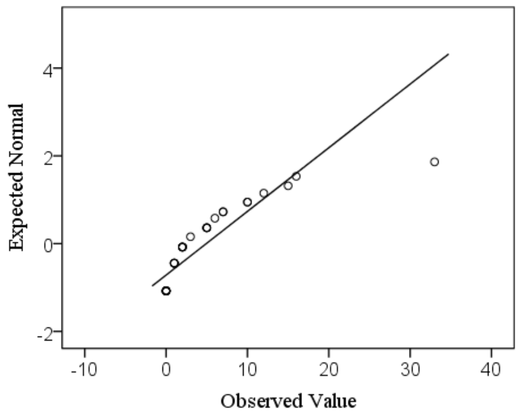
5.4.1.Visual Performance analysis

In an initial exploratory analysis, graphical (i.e. Quantile-Quantile (Q-Q) plots) and statistical (i.e. Shapiro-Wilk (S-W) and Kolmogorov-Smirnov (K-S) tests) revealed the violations against the assumption of normality. This was used to determine whether the mean average values were a good indication of the data and could be used for further analysis.

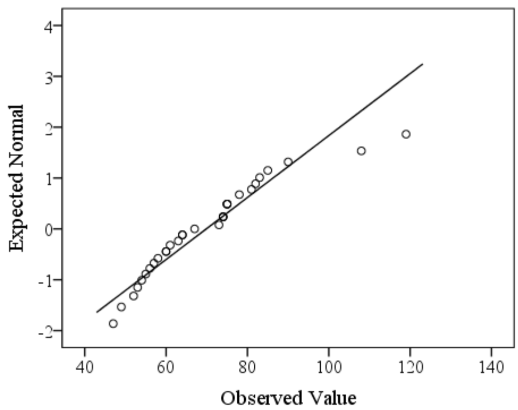
Figure 5.9 displays Q-Q plots for the error occurrences and time spent during achromatic acuity (AA) and chromatic acuity (CA) test under the clear window condition.



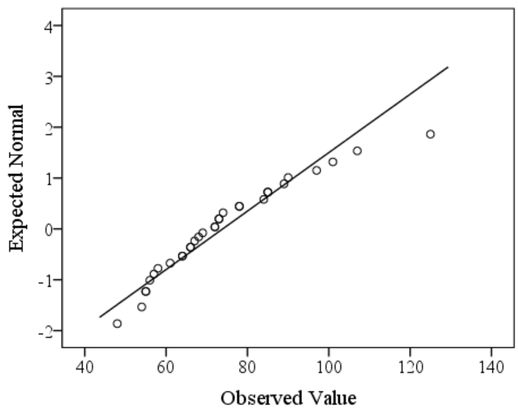
(a) Normal Q-Q Plot of Clear_AA



(b) Normal Q-Q Plot of Clear_CA



(c) Normal Q-Q Plot of Clear_AAt



(d) Normal Q-Q Plot of Clear_CAt

Figure 5.9: Q-Q plot showing the distribution of data for error occurrences and time spent when undertaking the tests about achromatic and chromatic acuity under the condition with the clear window

In Figure 5.9 (a), showing the data under the Clear_AA condition, the x-axis presents the number of error that occurred when participants performed the gap detection task for the 60 achromatic Landolt rings (observed value), while data on y-axis stands for the values expected to be when the distributions are normal (expected normal). A normal distribution is represented by the solid line running along the diagonal of the figure [189]. Since the plots in the figure show an S-shaped (deviating from the diagonal line), the distribution of this data would be negatively skewed away from the mean average value [189].

Tables 5.6 and 5.7 show the results of the K-S and S-W tests for time and errors measures under the three different window conditions, including test statistic, the degrees of freedom (df) and the statistically significant (*p*-value). Both K-S and S-W tests that can be used to check the distributions of the experimental data and the statistical difference from a normal distribution. Note that, *p*-values less than 0.05 indicate statistically significant differences between the distributions for the collected data in the experiment when the data is compared to a distribution that is normally distributed.

Table 5.6: Results of the Kolmogorov-Smirnov and Shapiro-Wilk tests for error occurrences in the three objective tests (achromatic acuity, chromatic acuity, and colour naming)

	Kolmogorov-Smirnov			**Shapiro-Wilk**		
Conditions	Statistic	df	*p*-value	Statistic	df	*p*-value
Clear_AA	0.27	31	0.00	0.67	31	0.00
TC_IL-Ni^{II}_AA	0.25	31	0.00	0.72	31	0.00
VO_2_Nano_AA	0.25	31	0.00	0.71	31	0.00
Clear_CA	0.23	31	0.00	0.71	31	0.00
TC_IL-Ni^{II}_CA	0.23	31	0.00	0.71	31	0.00
VO_2_Nano_CA	0.20	31	0.00	0.83	31	0.00
Clear_CN	0.22	31	0.00	0.77	31	0.00
TC_IL-Ni^{II}_CN	0.23	31	0.00	0.77	31	0.00
VO_2_Nano_CN	0.25	31	0.00	0.76	31	0.00

Table 5.7: Results of the Kolmogorov-Smirnov and Shapiro-Wilk tests for time spent on each of the three objective tests (achromatic acuity, chromatic acuity, and colour naming)

	Kolmogorov-Smirnov			Shapiro-Wilk		
Conditions	Statistic	df	p-value	Statistic	df	p-value
Clear_AAt	0.12	31	0.20	0.91	31	0.02
TC_IL-Ni^{II}_AAt	0.17	31	0.02	0.90	31	0.01
VO_2_Nano_AAt	0.18	31	0.01	0.95	31	0.20
Clear_CAt	0.14	31	0.16	0.95	31	0.13
TC_IL-Ni^{II}_CAt	0.14	31	0.16	0.96	31	0.23
VO_2_Nano_CAt	0.13	31	0.20	0.93	31	0.03
Clear_CNt	0.15	31	0.08	0.96	31	0.24
TC_IL-Ni^{II}_CNt	0.10	31	0.20	0.97	31	0.58
VO_2_Nano_CNt	0.12	31	0.20	0.95	31	0.12

Table 5.6 shows that the distribution of the number of errors in the AA, CA and CN tests under all experimental conditions are all significantly different from a normal distribution (p<0.05). In Table 5.7 for the same cases examined, the differences are not statistically significant (p>0.05) in 5 of the 9 cases when considering the time measurements recorded.

In both graphical and statistical tests, the data about the mean average value of the distribution were not normal, which violates one of the assumptions required by a parametric test (i.e., testing the differences in means across experimental groups) [189]. Since it was established that the mean was a poor predictor of the sampled data, non-parametric tests have been used that do not make any assumptions regarding the group distributions (i.e., whether they are normal or not) [190]. Therefore, to analyse the differences in visual performance (speed and time) across the independent variable (i.e. window conditions), the non-parametric Friedman's ANOVA test was applied.

When performing significance testing, the research question is outlined using two hypotheses: The Null (H_0) and the alternative (H_1) hypothesis. The null hypothesis states that rank scores (R) across the three experimental conditions (e.g., Clear, TC_IL-Ni^{II} and VO_2_Nano windows) are all equal, while conversely, the alternative states that the differences in the rank scores across the same conditions are not equal [Equations 5.2 and 5.3].

$$\mathrm{H_0}: \mathrm{R_{Clear}} = \mathrm{R_{TC\_IL-Ni^{II}}} = \mathrm{R_{VO_2\_Nano}} \quad \text{Equation [5.2]}$$

$$\mathrm{H_0}: \mathrm{R_{Clear}} \neq \mathrm{R_{TC\_IL-Ni^{II}}} \neq \mathrm{R_{VO_2\_Nano}} \quad \text{Equation [5.3]}$$

R is the sum of the ranks (i.e., since the distribution of sample values is not normal, ranking the values is the first step to deal with the values in each condition) for each condition.

The second assumption test was the homogeneity of variance. This was tested using the non-parametric Levene's test [191, 192]. These tests were used to determine whether the variances (i.e., the spread in the data) for both errors and time measurements across the three window conditions were significantly different from each other. In other words, when the variances are equal (i.e., homogeneous), the assumption has been satisfied, and the Friedman's ANOVA test can be used.

The effect size was calculated to overcome some of the limitations related to significant testing (i.e., such as in cases when using very small or large sample sizes) [193, 194]. The effect size is considered as a more reliable measurement of the magnitude of the effect that is examined (i.e., the larger the effect size, the bigger the influence of the window conditions on the time and error performance measures). In this analysis, the size of the effect used was the eta-squared (η^2) index [195, 196]. The interpretation of the effect size was based on the threshold recommended by Ferguson, whereby values corresponding to small (i.e. recommended minimum effect size (RMPE) ($0.25>\eta^2\geq0.04$), moderate ($0.64>\eta^2\geqslant0.25$) and strong ($\eta^2\geq0.64$) have been proposed [197].

Table 5.8 and Table 5.9 present the results of the Levene's test, showing for each condition, the test statistic (F), statistical significance (*p*-value), and the effect size. In all cases, the results show that the differences in the variance across all conditions examined are not significant ($p>0.05$) or of substantive effect size ($\eta^2<0.04$). The results show there are no reasons to suspect that the variances are different from each other, and therefore the assumption has been satisfied.

Table 5.8: Non-parametric Levene's test of homogeneity of variance of errors measurements under three window conditions for each task (AA, CA and CN)

Measurements	**F (2, 90)**	***p*-value**	η^2
AA	0.128	0.88	0.00
CA	0.658	0.52	0.01
CN	0.301	0.74	0.01

Table 5.9: Non-parametric Levene's test of homogeneity of variance of time measurements under three window conditions for each task (AA, CA and CN)

Measurements	**F (2, 90)**	***p*-value**	η^2
AAt	0.572	0.57	0.01
CAt	0.004	1.00	0.00
CNt	0.364	0.70	0.01

Since the Friedman's test can only be used to determine whether there is an overall difference between the window conditions, it cannot be used to isolate where the differences between the groups are. Therefore, when the initial (Friedman's) analysis detected statistical significance, *post-hoc* testing was used then used by performing multiple comparison tests (e.g., the Wilcoxon signed-rank) [198]. These compare the differences in the scores given between only two conditions, once the difference has been calculated, they will be ranked by assigning the sign of the difference (positive or negative) to the rank. The effect size of the differences was calculated to reveal the magnitude of the effect caused by independent variables.

5.4.2. Subjective data analysis

Since data were collected at an ordinal level of measurement using Likert scale questionnaires (i.e., ordinal data is data that could be placed into categories that can be ordered or ranked, but nothing about the difference of values from one rank to another), the non-parametric tests that are based on the ranks, median or range are more appropriate when handling this types of data as the dependent variable [190, 199].

In order to assess the subjective responses to the three window conditions, 16 questions were used to describe: lighting levels, colour temperatures, pleasantness, comfort, and naturalness. As explained in the experimental methods, a repeated-measures design was used.

Non-parametric Levene's test of homogeneity of variance was again calculated. The results have been reported in Table 5.10 indicate that differences in the variance across the conditions were not significant (p>0.05) in all cases examined, with the exception of the question 4 (Q4). However, the Brown Forsythe test (a modified Levene's test of homogeneity of variance based on absolute deviation for medians instead of means), indicated that the variances of Q4 were equal [200]. Therefore, the test showed evidence that the assumption of homogeneity of variance was satisfied (i.e., equal variances across the window conditions).

Table 5.10: Non-parametric Levene's test of homogeneity of variance of questionnaires

Questions	F (2, 90)	p-value	η^2
Q1	1.331	0.269	0.029
Q2	0.132	0.877	0.003
Q3	0.985	0.377	0.021
Q4	1.461[a]	0.238[a]	0.033
Q5	1.003	0.371	0.022
Q6	0.357	0.701	0.008
Q7	0.691	0.504	0.015
Q8	0.279	0.757	0.006
Q9	0.773	0.465	0.017
Q10	0.057	0.945	0.001
Q11	1.530	0.222	0.033
Q12	0.225	0.799	0.005
Q13	0.384	0.682	0.008
Q14	1.032	0.361	0.022
Q15	2.644	0.077	0.055
Q16	1.122	0.330	0.024

[a] Modified by Brown Forsyth test about homogeneity of variances

Friedman's ANOVA was also appropriate for investigating whether significant different assessments for the three window conditions would be given. To isolate the differences found within the initial Friedman's ANOVA test, Wilcoxon signed rank comparison was conducted as following *post-hoc* study.

5.5. Results and Analysis

5.5.1. Objective tests

5.5.1.1. Error occurrences of AA, CA and CN affected by different window conditions

Figure 5.10 shows that there are apparent differences in the median average values corresponding to a number of errors recorded in the AA task across three window conditions. While the other tasks do not appear to show any apparent differences in the median values across the three window conditions, the Clear condition shows the lowest errors, and the VO_2_Nano condition has the highest errors. Generally speaking, when participants performed the CA task under the Clear window condition, fewer errors were recorded when compared to the other two window conditions. While the medians of errors under VO_2_Nano and TC_IL-Ni^{II} window conditions appear to be the same.

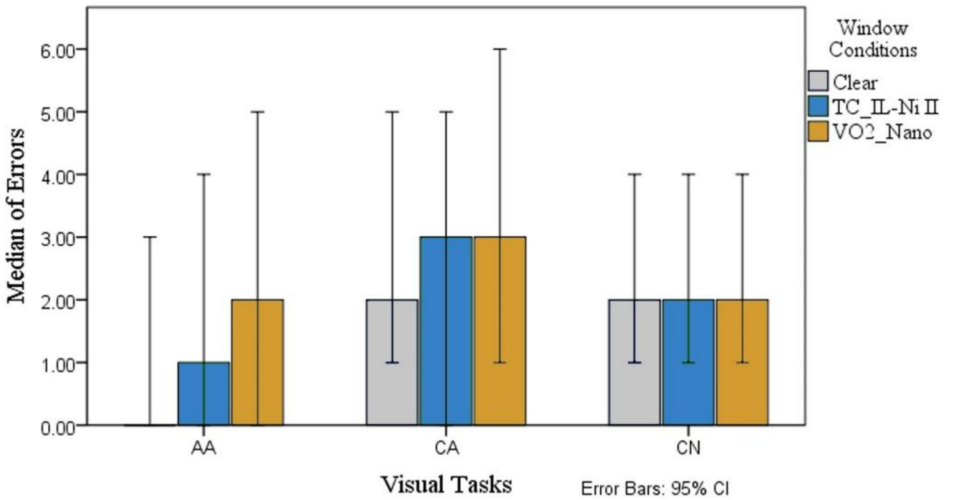


Figure 5.10: Comparisons between medians cumulative errors made under the three window conditions according to the achromatic acuity, chromatic acuity, and colour naming tasks, respectively. Error Bars show the 95% confidence intervals

Table 5.11 shows the results of the Friedman's ANOVA test for the average number of errors recorded when performing the Landlot rings across the different window conditions for each of the three tasks. The table presents the mean ranks, the median (M_{dn}) and inter-quartile range (IQR), number of participants (N), test statistic (χ^2) and *p*-value.

Table 5.11: Friedman test of error occurrences during AA, CA and CN test.

Task	Mean Rank	M_{dn} (IQR)	N	χ^2	*p*-value
Clear_AA	1.87	0 (5)			
TC_IL-Ni^{II}_AA	1.84	1 (5)	31	6.02	0.04
VO_2_Nano_AA	2.29	2 (5)			
Clear_CA	1.92	2 (7)			
TC_IL-Ni^{II}_CA	1.84	3 (6)	31	3.60	0.16
VO_2_Nano_CA	2.24	2 (6)			
Clear_CN	2.08	2 (4)			
TC_IL-Ni^{II}_CN	2.1	2 (4)	31	1.82	0.40
VO_2_Nano_CN	1.82	2 (5)			

The Friedman test detected a significant difference ($p<0.05$) when performing the achromatic Landolt ring task under the three window conditions. However, for the other two tasks – chromatic acuity and colour naming – no statistically significant differences were found.

The results indicate that, under illumination levels of 100 lux, the number of errors recorded under the achromatic Landolt ring task may be influenced by the range of colour temperatures (i.e., 4000-7000 K) created by the three different window conditions.

A *post-hoc* analysis was conducted in the following to isolate the main effects between variables using pairwise comparisons. The statistical difference of the pairwise comparison was calculated by Wilcoxon signed rank test. In order to reduce the risk of committing Type I errors when multiple pairwise tests were conducted under the same hypothesis, Bonferroni corrections were applied to adjust the alpha-level (e.g. the significance level of 0.05 [189]) [201]. The new alpha-level declaring statistical significance has been calculated as 0.05/3= 0.02, whereby 3 is the number of comparisons made.

The effect size was calculated for each pairwise comparison to determine the magnitude of the differences by using the Z-score from the Wilcoxon tests to estimate the Pearson's correlation coefficient, *r* according to the following equation [189]. According to the effect size interpretation suggestions by Ferguson [197], the small, moderate and large effect size ($0.2 \leq r < 0.5$, $0.5 \leq r < 0.8$ and $r \geq 0.8$), respectively.

$$r = \frac{Z}{\sqrt{N}} \qquad \text{Equation [5.4]}$$

Where, N is the number of observations in total for each pair of comparison.

Table 5.12 shows the Median (M_{dn}), and inter-quartile range (IQR) for the number of errors occurred when participant is telling the gap direction of each achromatic Landolt ring. The statistical significance (*p*-value), ranks of positive, negative and ties within each paired comparison are present, respectively.

Table 5.12: Wilcoxon signed-rank paired test of errors occurred on Achromatic Acuity under three light conditions

Conditions	M_{dn} (IQR)	M_{dn} (IQR)	*p*-value	Positive	Negative	Ties	Z	Effect Size (r)
TC_IL-Ni^{II}_AA vs. Clear_AA	1 (5)	0 (5)	0.92	9	10	12	-0.10	-0.01
VO_2_Nano_AA vs. Clear_AA	2 (5)	0 (5)	0.01	16	7	8	2.49	0.32*
VO_2_Nano_AA vs. TC_IL-Ni^{II}_AA	2 (5)	1 (5)	0.05	3	12	16	-1.97	-0.25*

The results show that the medians are different in each pair of comparison in terms of error occurrence in achromatic acuity test. However, the only difference found between window conditions of VO_2_Nano and Clear is statistically significant (i.e., *p*-value = 0.01 < 0.02 with Bonferroni corrections applied) and effect size is 0.31 (small effect).

The median average of the VO_2_Nano_AA is higher than case Clear_AA, with a higher number of positive rank. Therefore, under the VO_2_Nano window condition when performing the achromatic acuity task, more errors were made when compared to the clear window condition. For the comparison between VO_2_Nano and TC_IL-Ni^{II} window conditions, although the difference is not statistically significant, the effect size is small but practically significant (0.25). This also showed that fewer errors occurred under the TC_IL-Ni^{II} window condition than the VO_2_Nano window condition. When comparing the TC_IL-Ni^{II} and Clear window conditions, no statistically or practically significant difference was found.

Therefore, statistical analysis of the results about achromatic acuity indicates that the colour temperatures of window conditions influenced the number of errors recorded when participants recalled the gap directions of Landolt rings. This result is similar to previous research by Berman et al. [188], presenting that under the equal luminance levels and higher CCT lead to improved visual performance and higher visual acuity.

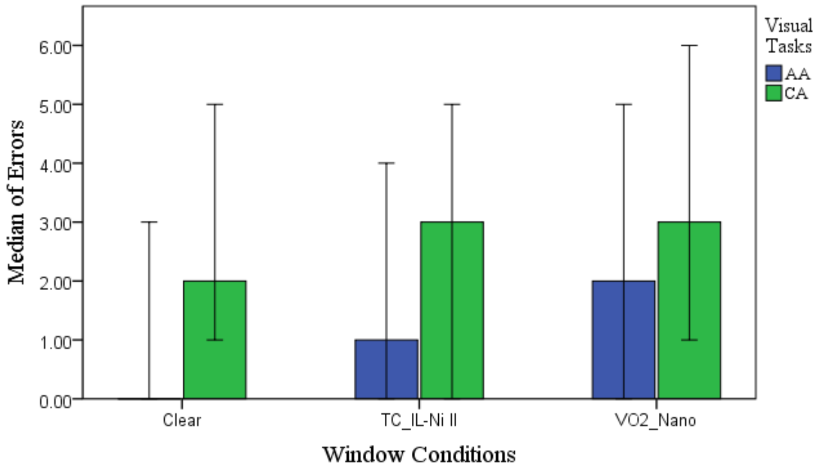


Figure 5.11. Medians of error occurrence number for achromatic acuity and chromatic acuity under three window conditions (Error Bars with a confidential interval of 95%)

Referring to the Figure 5.11, it is found that under the same window conditions, higher frequency of error occurred in CA tasks than AA tasks. Therefore, Wilcoxon paired comparisons were also conducted between achromatic and chromatic acuity test, in order to find out the effect of the window colours on acuity, as is shown in Table 5.13. It can be seen that medians of error occurrences on chromatic acuity are all higher than that of achromatic acuity.

The Wilcoxon tests show that in 2 out of the 3 cases, the differences across the visual tasks for the same window conditions are statistically significant, i.e. for Clear and TC_IL-Ni^{II}. These results reveal that more errors for gap directions of coloured Landolt rings were made by the participants under the Clear and TC_IL-Ni^{II} window conditions. This may be due to the luminance contrast of coloured Landolt rings are relatively lower than those in the achromatic chart. Therefore, the gaps in the coloured rings are relatively more difficult to be identified.

Table 5.13. Wilcoxon signed-rank paired test between errors occurred on Achromatic and Chromatic Acuity under three light conditions separately (alpha value is 0.05)

Conditions (M_1 vs M_2)	M_{1dn} (IOR)	M_{2dn} (IQR)	*p*-value	Positive	Negative	Ties	Z	Effect Size (r)
Clear_AA vs. Clear_CA	0 (5)	2 (7)	0.00*	3	15	13	-3.29	-0.42*
TC_IL -Ni^{II}_AA vs. TC_IL- Ni^{II}_CA	1 (5)	3 (6)	0.02*	5	16	10	-2.37	-0.30*
VO_2_Nano_AA vs. VO_2_Nano_CA	2 (5)	3 (6)	0.11	7	19	5	-1.62	-0.21*

While under the VO_2_Nano window condition, the difference between achromatic and chromatic acuity is not statistically significant (p>0.05), meanwhile, the r value falls in the range representing a small effect size. The results suggest that the number of errors recorded in the VO_2_Nano window condition on both chromatic and achromatic acuity is similar.

5.5.1.2. Time spent on AA, CA and CN tests affected by different window conditions

Figure 5.12 plots median average of the time recorded to complete each task under each window condition. On the y-axis, this shows the time spent in seconds under each test. On the x-axis, this shows the different type of tests conducted based on the different window conditions. Figure 5.12 shows, time spent differs for each type of tests based on the three window conditions.

During achromatic acuity test, the time taken to complete each of the tasks under the Clear window condition appear to be is higher than the other two, and VO_2_Nano results in the least time spent. While for chromatic acuity test, Clear window leads to more time spent than the other two. For the colour naming test, it is VO_2_Nano window condition that caused the participants to spend the longest time to complete the task.

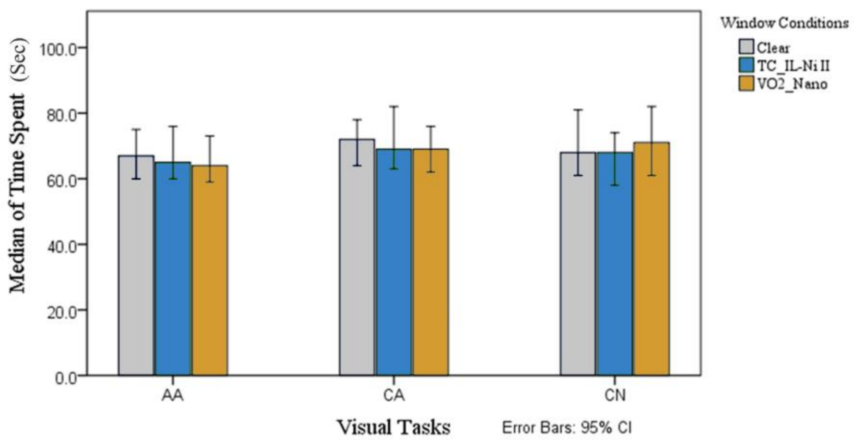


Figure 5.12: Comparisons between medians of time spent (unit is sec) on the achromatic acurity (AA), chromatic acuity (AA), and colour naming (CN) tasks under the three window conditions, respectively. Error Bars show the 95% confidence intervals

The significance of differences required further investigation by conducting Friedman's test as shown in Table 5.14. It can be seen that there is no statistically significant differences in all cases compared. Based on the results from this analysis, the time that was recorded when participants performed each of the tasks under the three different window conditions did not vary consideably. In otherwords, based on time measurements alone, there were no signifcant differences when considering the different window conditions.

Since there were statsitcally significant differences found in the initial Friedman's ANOVA tests, there was no need for any futher *post-hoc* testing.

Table 5.14: Friedman test of time spent on AA, CA, and CN test

	Mean Rank	M_{dn} (IQR)	N	χ^2	*p*-value
Clear_AAt	1.90	67 (21)			
TC_IL-Ni^{II}_AAt	2.26	65 (30)	31	3.16	0.20
VO_2_Nano_AAt	1.84	64 (19)			
Clear_CAt	1.95	72 (24)			
TC_IL-Ni^{II}_CAt	2.00	69 (27)	31	0.15	0.93
VO_2_Nano_CAt	2.05	69 (25)			
Clear_CNt	2.13	68 (28)			
TC_IL-Ni^{II}_CNt	1.92	68 (21)	31	0.81	0.67
VO_2_Nano_CNt	1.95	71 (27)			

In an alternative follow-up analysis, pairwise comparisons between time spent on achromatic and chromatic acuity under the Clear, VO_2_Nano and TC_IL-Ni^{II} window conditions were undertaken. It aims to investigate whether participants would spend different duration to identify gap directions of Landolt rings with different colours.

Figure 5.13 shows that median of time spent on achromatic acuity is lower than that of chromatic acuity under each lighting condition. Wilcoxon signed rank test were carried out to detect the significance of graphical inspected difference.

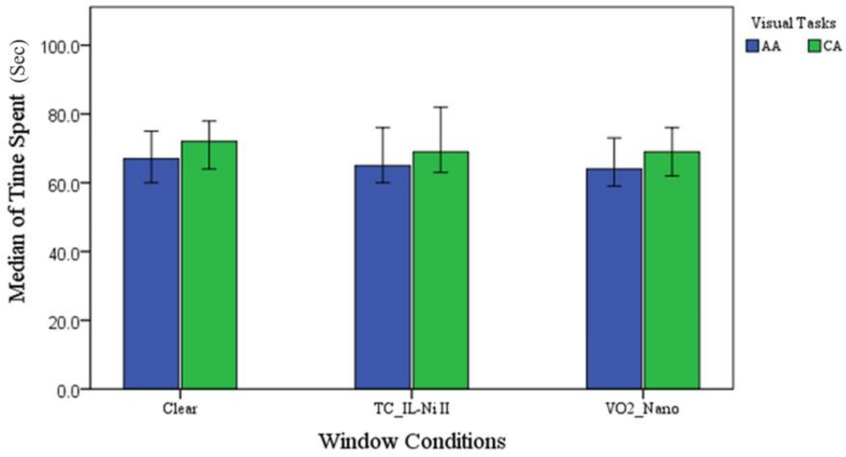


Figure 5.13: Bar chart of time spent (unit is sec) on achromatic and chromatic acuity under three window conditions with error bar (confidential interval is 95%)

Table 5.15 reports the ranks, significance and effect size for each pair of comparison, and 2 out of the 3 cases reveal that the differences are statistically significant under the clear and VO_2_Nano window conditions and with small effect sizes.

Table 5.15: Wilcoxon signed-rank paired test of time spent on Achromatic and Chromatic Acuity under three light conditions separately (alpha value is 0.05）

Conditions (M_1 vs M_2)	M_{1dn} (IOR)	M_{2dn} (IQR)	p-value	Positive	Negative	Ties	Z	Effect Size (r)
Clear_CAt vs. Clear_AAt	72 (24)	67 (21)	0.03	18	11	2	-2.165	-0.28*
TC_IL-Ni^{II}_CAt vs. TC_IL-Ni^{II}_AAt	69 (27)	65 (30)	0.37	15	12	4	-0.891	-0.11
VO_2_Nano_CAt vs. VO_2_Nano_AAt	64 (19)	64 (19)	0.01	21	9	1	-2.790	-0.35*

***small effect; ** moderate effect; *** large effect**

Due to the negative sign of the effect size, this shows that under both Clear and VO_2_Nano window conditions, participants spent more time on chromatic acuity test than achromatic one. However, under the TC_IL-Ni^{II} window condition, the difference is non-significant, signalling that time spent on achromatic and chromatic acuity tests are almost the same.

To summarise the findings from Table 5.13 and Table 5.15, the participants spent long time for the chromatic acuity test, and more errors occur when comparing with achromatic acuity. However, under the TC_IL-Ni^{II} window condition, participants spend similar time for both tests. This indicates that cool (bluish) lighting environment (i.e., a higher colour temperature) provided by TC_IL-Ni^{II} window has little effect on the participant to carry out work tasks with increasing difficulty, i.e., reducing contrasts in this study. On the other hand, warm (reddish/yellowish) window provided by VO_2_Nano window are likely to make people less arousal during working. This is similar to previous research that environment with higher CCTs is more appropriate for work [150-152]. Therefore, the experiment provided additional evidence that under the environment with higher CCTs, it is beneficial to keep the equal arousal to do different work rather than that under the environment with lower CCTs.

5.5.2. Analysis of questionnaires

5.5.2.1. Subjective assessment affected by three window conditions

Table 5.16 shows the results from Friedman's ANOVA tests for each of the 16 questions, the mean ranks, median, IQR, mode, minimum and maximum values for each questionnaire response given under each window condition, the test statistic (χ^2), and statistical significance (*p*-value).

Table 5.16: Friedman test for 16 questionnaires

Questions	Conditions	Mean Rank	M_{dn} (IQR)	Mode	Min.	Max.	χ^2	*p*-value
Q1	Clear	2.150	3 (1)	2	2	5	2.755	0.252
	TC_IL-Ni^{II}	1.980	2 (1)	2	1	4		
	VO_2_Nano	1.870	2 (1)	2	2	4		
Q2	Clear	1.970	4 (2)	4	1	4	1.258	0.533
	TC_IL-Ni^{II}	1.920	3 (2)	4	1	5		
	VO_2_Nano	2.110	3 (2)	4	1	5		
Q3	Clear	2.060	3 (1)	2	2	4	0.700	0.705
	TC_IL-Ni^{II}	2.030	3 (2)	2	1	5		
	VO_2_Nano	1.900	2 (1)	2	1	5		

Q4	Clear	2.000	2 (1)	2	1	4		
	TC_IL-Ni^{II}	1.560	2 (1)	2	1	4	16.022	0.000*
	VO_2_Nano	2.440	3 (2)	4	1	5		
Q5	Clear	2.240	3 (1)	2	1	5		
	TC_IL-Ni^{II}	1.770	2 (1)	2	1	5	6.029	0.049*
	VO_2_Nano	1.980	2 (1)	2	1	5		
Q6	Clear	2.050	4 (2)	5	2	5		
	TC_IL-Ni^{II}	1.870	4 (1)	4	2	5	1.661	0.436
	VO_2_Nano	2.080	4 (2)	5	2	5		
Q7	Clear	1.850	2 (1)	2	1	4		
	TC_IL-Ni^{II}	2.160	2 (1)	2	1	4	2.984	0.225
	VO_2_Nano	1.980	2 (1)	2	1	4		
Q8	Clear	2.080	2 (1)	2	1	4		
	TC_IL-Ni^{II}	2.030	2 (1)	2	1	4	1.733	0.420
	VO_2_Nano	1.890	2 (0)	2	1	4		
Q9	Clear	2.110	2 (1)	2	1	5		
	TC_IL-Ni^{II}	1.790	2 (1)	2	1	5	4.233	0.120
	VO_2_Nano	2.100	2 (1)	2	1	5		
Q10	Clear	2.030	3 (2)	2	1	5		
	TC_IL-Ni^{II}	1.950	2 (2)	2	1	5	0.206	0.902
	VO_2_Nano	2.020	3 (2)	2	1	5		
Q11	Clear	2.230	3 (2)	2	1	5		
	TC_IL-Ni^{II}	1.820	2 (1)	2	1	5	4.794	0.091
	VO_2_Nano	1.950	2 (1)	2	1	5		
Q12	Clear	2.030	3 (1)	2	1	5		
	TC_IL-Ni^{II}	2.050	3 (2)	2	1	5	0.437	0.804
	VO_2_Nano	1.920	3 (1)	3	1	5		
Q13	Clear	1.950	3 (1)	3	1	5		
	TC_IL-Ni^{II}	1.950	3 (2)	2	2	5	0.771	0.680
	VO_2_Nano	2.100	4 (2)	4	2	5		
Q14	Clear	2.110	2 (1)	2	1	4		
	TC_IL-Ni^{II}	1.760	2 (1)	2	1	4	4.630	0.099
	VO_2_Nano	2.130	2 (1)	2	1	5		
Q15	Clear	2.100	2 (1)	2	1	4		
	TC_IL-Ni^{II}	1.680	2 (0)	2	1	5	8.541	0.014*
	VO_2_Nano	2.230	2 (1)	2	1	5		
Q16	Clear	2.190	2 (3)	2	1	5		
	TC_IL-Ni^{II}	1.660	2 (1)	2	1	4	9.940	0.007*
	VO_2_Nano	2.150	2 (1)	2	1	5		

*significant

To remind, 5-point Likert scales were employed, whereby ‘1’ represents the most negative response to the questions, and ‘5’ stands for the most positive response to the questions. In the neutral point in the scale (e.g., the third point), this did not correspond to neither a positive nor a negative response to the questionnaire answer given by a test subject.

It can be seen from the results that, the medians for most of the questions corresponding to a score of 2 (negative response), several of them got the answer of 3 (neither positive nor negative), while just a few of them obtained a score of 4 (positive response). The distribution of median averages indicated that participants evaluated the three window conditions using negative or neutral responses, but with some questionnaire responses rating the conditions positively. For instance, the brightness was assessed by Q1, 2 out of the 3 window conditions were given a score of 2, which means they were perceived slightly dark. While Q6 about rating the difficult degree of doing tasks, a score of 4 was the median average for all three condition, which means that, tasks were considered as easy to complete.

The Friedman’s ANOVA test detected significant differences ($p<0.05$) across the three window conditions in 4 out of 16 questions examined. These questions described subjective assessment relating to the environment colour temperatures (Q4), naturalness (Q5), general comfort (Q15) and subjective acceptance (Q16). This shows that the responses given in each of these questions varied across the three different window conditions.

To isolate the main difference caused by these three window conditions, post hoc investigation was undertaken using Wilcoxon signed-rank paired comparison across the significant questions, as is shown in Table 5.17. Based on the Bonferroni correction, the statistical significance was calculated as 0.02. Therefore, values of *p*-values below this new threshold are declared to be statistically significant.

Table 5.17: Wilcoxon signed-rank pairwise comparison test with significant results

Questions	Conditions (M_1vsM_2)	M_{1dn} (IQR)	M_{2dn} (IQR)	p-value	Positive	Negative	Ties	Z	Effect Size (r)
Q4	TC_IL-Ni^{II} vs. Clear	2 (1)	2 (1)	0.03	5	16	10	-2.172	-0.28*
	VO_2_Nano vs. Clear	3 (2)	2 (1)	0.01	15	4	12	-2.747	-0.35*
	VO_2_Nano vs. TC_IL-Ni^{II}	3 (2)	2 (1)	0.00	20	4	7	-3.565	-0.45*
Q5	TC_IL-Ni^{II} vs. Clear	2 (1)	3 (1)	0.01	3	13	15	-2.595	-0.33*
	VO_2_Nano vs. Clear	2 (1)	3 (1)	0.39	7	12	12	-0.856	-0.11
	VO_2_Nano vs. TC_IL-Ni^{II}	2 (1)	2 (1)	0.14	9	5	17	-1.496	-0.19
Q15	TC_IL-Ni^{II} vs. Clear	2 (0)	2 (1)	0.03	5	13	13	-2.128	-0.27*
	VO_2_Nano vs. Clear	2 (1)	2 (1)	0.46	9	7	15	-0.734	-0.10
	VO_2_Nano vs. TC_IL-Ni^{II}	2 (1)	2 (0)	0.03	15	3	13	-2.173	-0.28*
Q16	TC_IL-Ni^{II} vs. Clear	2 (1)	2 (1)	0.02	2	13	16	-2.392	-0.30*
	VO_2_Nano vs. Clear	2 (3)	2 (1)	0.62	7	8	16	-0.500	-0.06
	VO_2_Nano vs. TC_IL-Ni^{II}	2 (3)	2 (1)	0.15	13	3	15	-1.446	-0.18

***small effect; ** moderate effect; *** large effect**

For Q4 related to the discrimination of colour temperatures, 2 out of the 3 cases present statistically significant differences. For the VO_2_Nano window, a higher median value is seen as compared to the Clear window condition, and VO_2_Nano window also got higher median than the TC_IL-Ni^{II} window. For these two cases of comparison, the effect sizes of the difference reported were small but practically significant. This means that the VO_2_Nano window condition was assessed to be warmer coloured than Clear and TC_IL-Ni^{II}, respectively.

For the pairwise comparison between TC_IL-Ni^{II} and Clear window, although the difference is not statistically significant, a notable effect size representing a small effect was also detected. Rosenthal *et al.* [202] suggest that a non-significant *p*-value and but practically significant effect size may indicate that larger sample size is required, to reject the null hypothesis (i.e., increasing the statistical power of the test). Therefore, the overall results from Q4 indicated that, in the dark illuminance environment (i.e., 100lux), participants are able to discriminate the change of colour temperatures (i.e., measured ranging from 4000K to 7000K) caused by the three window conditions.

For Q5 relating the naturalness of the visual chart (i.e., Landolt rings) affected by the window conditions, only 1 out of the 3 cases has a significant difference. The TC_IL-Ni^{II} window has a lower median than Clear window condition, revealing that blue-tinted condition leads to an appearance considered to be more artificial than under the Clear window conditions, with a small effect ($0.2<r<0.5$).

Q15 present the overall comfort regarding the three window conditions, two pairs of comparison (i.e., TC_IL-Ni^{II} vs Clear, and VO_2_Nano vs TC_IL-Ni^{II}) were detected having small effect with a nonsignificant difference. A higher negative rank for comparison of TC_IL-Ni^{II} vs Clear, and a higher positive rank for comparison of VO_2_Nano vs TC_IL-Ni^{II} means that the TC_IL-Ni^{II} window condition is relatively less comfortable than the other two.

For Q16 about acceptance of these three conditions, only 1 out of the 3 cases was reported to have a small effect and non-significant difference, which is the comparison between TC_IL-Ni^{II} and Clear window conditions. A higher negative rank indicates TC_IL-Ni^{II} is relatively less acceptable. Both Q15 and Q16 are related to overall assessment about the window conditions, revealing that the TC_IL-Ni^{II} window condition is the most unacceptable one, and this result might be more significant with increase sample size.

Table 5.18: Wilcoxon signed-rank pairwise comparison test with a non-significant difference, but the notable effect size

Questions	Conditions (M_1-M_2)	M_{1dn} (IQR)	M_{2dn} (IQR)	p-value	Positive	Negative	ties	Z	Effect Size (r)
Q1	TC_IL-Ni^{II} vs. Clear	2 (1)	3 (1)	0.12	4	7	20	-1.558	-0.20
	VO_2_Nano vs. Clear	2 (1)	3 (1)	0.05	4	10	17	-2.000	-0.25*
	VO_2_Nano vs. TC_IL-Ni^{II}	2 (1)	2 (1)	0.51	5	7	19	-0.660	-0.08
Q9	TC_IL-Ni^{II} vs. Clear	2 (1)	2 (1)	0.06	5	12	14	-1.882	-0.24*
	VO_2_Nano vs. Clear	2 (1)	2 (1)	0.87	7	7	17	-0.166	-0.02
	VO_2_Nano vs. TC_IL-Ni^{II}	2 (1)	2 (1)	0.05	8	2	21	-1.998	-0.25*
Q11	TC_IL-Ni^{II} vs. Clear	2 (1)	3 (1)	0.02	4	12	15	-2.372	-0.30*
	VO_2_Nano vs. Clear	2 (1)	3 (1)	0.25	4	10	17	-1.147	-0.15
	VO_2_Nano vs. TC_IL-Ni^{II}	2 (1)	2 (1)	0.34	10	7	14	-0.948	-0.12

***small effect; ** moderate effect; *** large effect**

Although Friedman's ANOVA did not show significant difference detected in the brightness (Q1), working tolerance (Q9), and pleasantness (Q11), Wilcoxon signed rank paired comparison detected a small effect with a non-significant difference, as is reported in Table 5.18. The results indicate that although VO_2_Nano window yields a relatively dark, participant still prefer to spend longer time to work in VO_2_Nano lighting condition especially when comparing with the TC_IL-Ni^{II} one. In addition, participants perceived more unpleasant in the environment with TC_IL-Ni^{II} window. These conclusions are consistent with previous research [17, 21]

5.6. Summary and discussion

Under an illuminance of 100 lux on a vertical target surface (i.e., the visual task), artificial daylight produced through TC_IL-Ni^{II}, VO_2_Nano and Clear windows created differences in visual performance and subjective appearance. To investigate an experiment was conducted under controlled conditions with the test subjects performing a series of visual tasks in a space with these three window configurations.

5.6.1. Visual performance

Results indicated that, in achromatic acuity (AA) task errors, made are relatively lower under the VO_2_Nano window condition than Clear and TC_IL-Ni^{II} window conditions, especially, the difference between VO_2_Nano and Clear windows are more significant. Fotios' and Boyce's [20, 165] studies indicated that different light spectrum did not affect human performance on achromatic acuity tasks. However, the study conducted by Berman *et al.* [188] present that at the low luminance level, visual acuity is better under higher CCT lighting conditions, because the pupil size would reduce stimulated by higher CCT light, and reduced pupil size improves human eye's higher visual acuity and contrast sensitivity.

In this study, it is suspected that errors in AA task are not only related to the visual acuity physically, i.e., quality of participant's eyes, but also related to their alertness, arousal and concentration levels to do each task affected by different window conditions. Previous research indicated that environment with higher CCT is helpful to improve alertness [203, 204], and 6500K of CCT is beneficial to improve concentration [205].

In terms of chromatic acuity (CA) tasks, no significant difference was detected across the three window conditions. However, when comparing the errors occurred between achromatic and chromatic acuity test under each condition respectively, participants present significantly more errors in the CA task than the AA one.

Compared with Clear and TC_IL-Ni^{II} window conditions, notable more errors in CA task were made under VO_2_Nano window conditions (i.e., non-significance with meaningful effect size). It is because of the lower contrasts of coloured Landolt rings than black ones, which provide additional challenge to identify the gap directions of Landolt rings under this low illuminance environment.

In the CN task, colour discriminations of red, green and blue did not show significant difference across three window conditions. However, it is worth to mention that errors mainly occurred between green and blue, almost every participant has the problem to confound these two colours, especially at the small size. It is because of the similar spectral reflectance of green and blue rings shown in Figure 5.8, which increases the difficulty for human eyes to tell the difference between reflected lighting within similar wavelength ranges.

Time spent on completing tasks indicate two main issues in this study: 1) productivity under certain conditions, 2) stability of doing different tasks. It is reported that participants almost spent equal time to do the same tasks across the three windows conditions. This means that the TC_IL-Ni^{II} and VO_2_Nano windows have the potential to keep productivity to do the same work. However, when the difficulty of task level was improved, i.e., comparing between time spent on achromatic and chromatic acuity tests, only TC_IL-Ni^{II} present non-significant difference between the two tasks. This means that participants could keep their speed of doing more challenging tasks under TC_IL-Ni^{II} window condition (i.e., higher CCT of 7000 K). This also means that higher CCT environment is beneficial to keep efficiency to work, and this result is consistent with previous research [203, 204].

5.6.2. Subjective assessment

Subjective assessment shows that even in the low illuminance environment (100 lux) participants could discriminate the variation of CCT (4000-7000 K) caused by TC windows. TC_IL-Ni^{II} window condition would lead to a more unnatural visual of coloured targets inside the room, compared with the other two window conditions.

$TC\_IL\text{-}Ni^{II}$ is less comfortable and acceptable than VO_2_Nano and Clear window conditions. Additionally, participants would like to spend a long time to work in the VO_2_Nano window condition compared with the $TC\_IL\text{-}Ni^{II}$ one. Previous research also supports this conclusion, which indicated an environment with warmer CCT is more desirable [17, 18, 21, 153].

To sum up, the subjective rating and objective task results present incompatible conclusions. Participants could work better under $TC\_IL\text{-}Ni^{II}$ window conditions, while they prefer to working in the room with VO_2_Nano window subjectively. Therefore, it is essential to know the most important point (i.e., depending on the work types and precision requirement) for a specific office building and chose the suitable tinted smart windows accordingly.

Chapter 6

Human Response to Potentially Developed Tinted TC Windows

6.1. Introduction

Thermochromic (TC) windows have received a lot of recent attention to better understand how they may be used to provide dynamic spectral solar control. Various TC materials have been developed for application within buildings, offering both energy conservation and desirable daylighting distribution [10, 16, 66, 99]. Vanadium dioxide based TC materials are able to alternate the sometimes undesirable near infrared components of solar radiation and admit visible wavelengths into a building [12, 14, 16, 98]. Ionic liquid based composite film of TC materials mainly allow for the adjustment of how much visible solar radiation is transmitted [9, 96]. In addition to modifying the amount of radiation transmitted, TC materials also exhibit a degree of selective absorption resulting in the transmitted light being also tinted, typically yellow/brown or blue/green. As both the quality and quantity of transmitted light can be affected by TC materials factors such as correlated colour temperature (CCT) and illuminance distribution which should be considered when employing TC windows to illuminate the interiors of buildings. These factors will also affect how building users experience views out of buildings onto their surroundings.

Recommended illuminance levels from CIBSE guide, mentioned that illuminance levels for working and learning environments range between 300-500lux [106]. However, there is no standard to inform appropriate CCTs from daylight sources. Commonly used classification of CCT for artificial light sources is: warm (<3300K), intermediate (3300K<CCT< 5300K), and cold (CCT>5300K) [106], and research studies have been conducted to explore the human visual performance in environments illuminated with different CCT light sources. Although illuminance levels dominate occupants' perception of brightness and determine the acceptability of the luminous environment in an office environment, CCT also has the potential to affect the performance of visual tasks and subjective ratings of naturalness, arousal, and pleasantness [148, 161, 165]. The findings on the influence of CCT are not univocal because of the limitations of the experiments and variability of human response, however, one result that is consistent in studies is that higher CCT tends to be perceived as unpleasant when used to provide high illuminances [133].

Studies have been undertaken to evaluate the effects of CCT on sustained attention of human subjects in an office environment illuminated using light sources with different CCT [203, 205-210]. The early studies tested the visual performance, cognitive ability, mood, etc. at 500lux, and it was found that there was no significant difference on performance when sources with CCT ranging from 3000K to 5000K were used [206, 207]. A study carried out by Rautkyla [203], with undergraduate students as participants indicated that different CCTs (4000K and 17000K) and prior exposure to daylight affect the alertness. Additionally, seasonal differences were discovered: during the spring, CCTs has less effect on alertness, while in the autumn, the17000K source induces more alertness than the source with a CCT of 4000K. Recently, Sleegers *et al.* [205] conducted a study on concentration using students completing tasks under three levels of CCT (i.e., 2900, 6500 and 12000K). It was found that the source with a CCT of 6500K resulted in higher levels of concentration, as compared with the tests conducted under 2900K and 12000K light sources. Moreover, Shamsul *et al.* [208] conducted a research exploring how visual task performance and subjective comfort are affected by sources with CCTs of 3000K, 4000K and 6500K. They concluded that higher CCTs can lead to increased alertness and work better for academic activities such as typing. Huang *et al.* [209] presented subjects with the Chu attention test under CCT conditions of 2700K, 4300K, and 6500 K, and found that 4300K environment result in better sustained attention. A recent study investigated individuals' performance and physiology under the influence of light sources with CCTs of 2700K and 6000K at 500lux at different times of the day (morning and afternoon) [210]. Their results showed that, exposing subjects to the environment with the higher CCT of 6000K gave the participants more vitality, however, the warmer lighting condition (i.e., CCT of 2700K) provided a more positive rating in terms of mood.

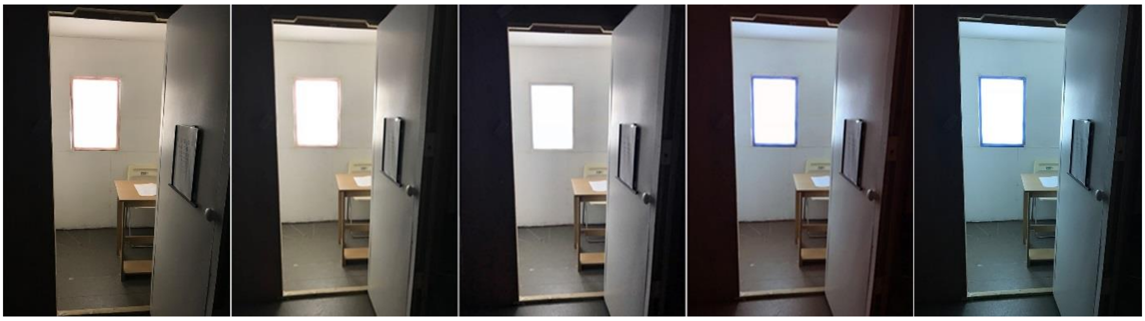
Based on the literature, it may be concluded that there is a requirement to better understand the acceptability of TC windows, and there is a need to understand how the significant change in CCT that occur between tinted states affected the occupants of the spaces they serve. Research into how sustained attention is affected by different CCT conditions is limited, but crucial to understand how TC windows will affect productivity of work and learning. Therefore, a multi-measure approach was designed in this study. The indoor conditions affected by two typical TC windows were simulated under desirable illuminance levels (approximately 300lux) for an office type working environment. The window types selected were based on VO_2 TC materials tinting to a brownish hue, and ionic liquid based TC materials tinting to be bluish hue. These were tested: an original tinted state and a deeper tinted state after switching. For practical reasons, filters matched the TC color temperatures were used in the experiments in place of window units. In addition, a clear window was used to serve as a reference. Under the five window conditions, two visual tasks (d2 test of attention and Landolt rings test), and subjective assessment using questionnaires (i.e., relating to brightness, visual comfort, alertness, pleasantness, etc.) were carried out by repeated measures within the same groups of participants. This experiment aimed to determine whether visual performance, sustained attention and subjective ratings were affected under the five different windows conditions.

6.2. Experimental Method

A repeated measures experiment, using the same group of participants to test different experimental conditions, was designed in this study to explore how visual performance and comfortable, as well as sustained attention are influenced by different thermochromic windows under different switching states. Under each of the different window conditions, the performance of participants was assessed in two: 1) Objective visual tasks contains to determine achromatic visual acuity, colour discrimination, and attention. 2) Subjective assessment of the daylight environment investigated through participants completing 5-level Likert scale questionnaires, detecting visual comfort, brightness, alertness, naturalness, and pleasantness.

6.2.1 Experiment set up

A test room cubicle is a mock-up office cell with dimensions of 1.5m ×1.2m × 2.1m (width ×length × height) was constructed in the laboratory of Energy Technologies Building, at the University of Nottingham, UK. The size of experimental chamber is approximately 1/3 of a typical minimum working space (11m^2), meeting the requirement for models designed for use in participant studies where subjects are expected to perceive and provide an assessment of daylight environment [157, 176].The experimental chamber was lit by a simulated window system (a diffuse illuminated by an array of six LED lights), which provided artificial skylight. More information on the artificial window design can be found in section 5.3.



a. VO_2_S b. VO_2_U c. Clear d. IL_U e. IL_S

Figure 6.1: Photos of five lighting conditions as independent variables in this experiment

Table 6.1: Vertical and horizontal illuminance under five coloured lighting conditions

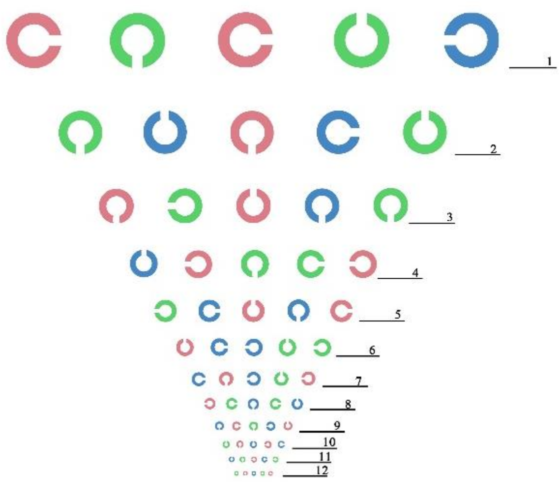
		Vertical surface		Horizontal surface	
		Illuminance (lux)	CCT (K)	Illuminance (lux)	CCT (K)
a.	**VO_2_S**	350 (±5%)	3410	300 (±5%)	3295
b.	**VO_2_U**	350 (±5%)	4053	300 (±5%)	3981
c.	**Clear**	350 (±5%)	4903	300 (±5%)	4827
d.	**TC_U**	350 (±5%)	6934	300 (±5%)	6704
e.	**TC_S**	350 (±5%)	10997	300 (±5%)	10557

Under the controlled illuminance levels, five types of TC window states were setup, producing the indoor lighting conditions shown in Figure 6.1. Illuminance levels on the wall opposite the window where the visual tasks were mounted were kept at approximately 350 lux. While the illuminance levels at desktop height in the middle of the room were around 300lux. According to guidance for lighting at work [211], the average illuminance for tasks requiring perception of detail is 200lux, and for fine details the illuminance is recommended to be 500lux. This is echoed by CIBSE who recommend the illuminance levels for office tasks to be between 300-500lux [106]. In this study, an illuminance of 300lux was selected, seeking to provide the participants with a relatively comfortable luminous environment appropriate for office based tasks. It is believed that, under these levels of illumination, the colour temperatures associated with the different types of window would influence subject perception of the luminous environment [212].

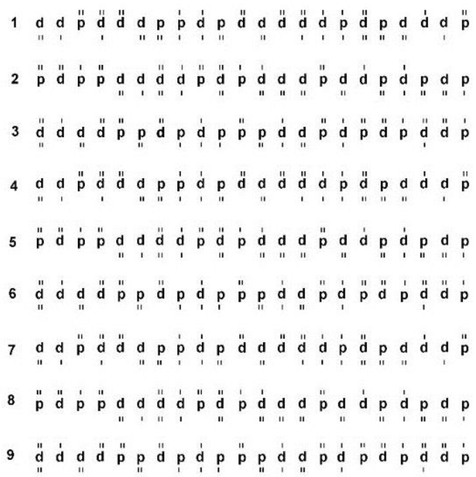
Referring to Section 5.3.1 (see Figure 5.4), the bronze and blue coloured window films used in this study have similar photometric properties found in the VO_2-based (VO_2_Nano) and ionic liquid based (TC_IL-Ni^{II}) thermochromic materials, respectively. The un-switched state was represented by using a single layer of tinted film and second layer was added to represent the switched state. The CCTs produced by the different window conditions were measured using a Konica Minolta CL-200A Chroma meter, and are presented in Table 6.1.The following conditions were presented to the subjects: 1) Clear window without any window film (i.e. Clear); 2) Window plus a single bronze window film whose spectral transmittance is close to that of the VO_2-based nanoparticle thermochromic materials, which tint to be a warm colour (CCT ≈ 4000K) (i.e.,VO_2_U); 3) Window plus a single blue coloured window film, whose spectral transmittance is similar to ionic liquid based thermochromic material, which has the feature of mainly changing the visible transmittance and tinting to blue at higher temperatures (CCT≈7000K) (i.e., IL-U); 4) and 5) were further switched versions of 2) and 3) respectively, and were produced by doubling the thickness of film, yielding CCTs of 3300K (i.e., VO_2_S) and 11000K (i.e., IL-S).

6.2.2. Objective tasks

Three objective tasks were used in this experiment were selected to investigate the achromatic acuity, colour discrimination and sustained attention respectively under the five window conditions. The colour test design was informed by the study of Fotios [165]. Chromatic acuity and colour discrimination were carried out using Landolt rings, coloured green (x=0.401, y=0.323), blue (x=0.219, y=0.231) and red (x=0.401, y=0.323), an example of the chromatic Landolt rings chart is shown in Figure 6.2 (a). There are 12 rows of Landolt rings with size decreasing from 8.0M to 0.63M (where, M-units specifies the height of typeset materials, 1 M= 1.5 mm) from up to the bottom, and the decrease gradient is 0.1 log unit per row. Each row has 5 rings with different colours and positions of the gap (left, right, up and bottom). Table 6.2 provides the contrasts produced under the simulated daylighting through the five window conditions respectively, which were calculated by Equation 5.1. It is found that under TC_IL-Ni^{II} window conditions, green and blue rings has relative lower contrast than red ones, while under VO_2_Nano window conditions, the red rings has relative lower contrast than other two. Chromatic Acuity was measured by encouraging the participants to make a best guess as to the position of the gaps in the circles, and their performance was scored as the number of errors. Colour Naming (CN) (i.e., discrimination of the different coloured rings) was also measured using the same chart. Participants were required to identify the colours of each ring, and subject performance was also scored using the number of errors. Based on the results of a pilot test undertaken by 5 subjects, there is no significant difference of achromatic acuity observed under the different window conditions (Please see section 5.3.1 for more details).



(a) Chart of chromatic Landolt rings



(b) Partially paper of d2 test

Figure 6.2: (a) Chromatic Landolt rings for achromatic acuity and colour naming test; (b) d2 test for attention

Table 6.2: Background and target (green, red and blue rings) luminance, as well as corresponding calculated contrast. (Lv **(**unit is cd/m^2**)** stands for luminance measured at the position of observer, and C is the contrast ratio)

	Ring colours	VO_2_S		VO_2_U		Clear		TC_U		TC_S	
		Lv	**C**	**Lv**	**C**	**Lv**	**C**	**Lv**	**C**	**Lv**	**C**
L_t	Green	37.03	-0.59	37.67	-0.59	38.92	-0.57	39.79	-0.56	38.99	-0.54
	Red	46.42	-0.49	44.49	-0.52	39.47	-0.57	40.08	-0.56	36.42	-0.57
	Blue	25.19	-0.72	25.16	-0.73	27.26	-0.70	28.12	-0.69	27.56	-0.67
L_b	Background	91.39		92.42		90.85		90.2		84.52	

Figure 6.2 (b) shows the d2 attention task employed in this experiment. It was first created in Germany by Brickenkamp as a cancellation task [213], which has been proposed as a useful neuropsychological measurement of sustained attention, concentration processes, and visual scanning speed [214]. The d2 test is conducted using paper and pencil, and subjects are asked to cross out any target letter, e.g., the ‘d’ with two dashes placed above and/or below the character, while ignoring all non-target characters (i.e. a ‘d’ with more or fewer than two dashes, and ‘p’ with any dashes) that are interspersed around it. Figure 6.2 (b) shows an example of part of the d2 test page. A full version of the d2 test has 14 trails in total with 47 characters in each row. Participants were asked to carry out each trail within 20 seconds, and move to next trail without pausing when 20 seconds were up.

The performance of the d2 test was sored using the descriptions in Table 6.3 [197], For these, TN indicates can be used as an indication of the speed of visual scanning, and EO, EC, TE, and PE are significantly related to accuracy. While CP gave the measures significantly correlated with both speed and accuracy, presenting that higher CP stands for higher quality of concentration.

Table 6.3. Abbreviations (abbr.), description, and calculation of d2 test of attention measures

In text abbr.	Description of measures	Computation
TN	Total number of characters processed	Sum of number of characters processed before the final cancellation on each trial
EO	Errors of omission	Sum of number of target symbols not cancelled
EC	Errors of commission	Sum of number of non-target symbols cancelled
TE	Total errors	Sum of all errors of omission and commission
CP	Concentration performance	Total number of correctly cancelled minus total number incorrectly cancelled
PE	Percent of errors	Total number of errors divided by the total number of characters processed

6.2.3. Subjective assessments

The questionnaires used in this part of study consisted of two parts. Part I focused on the human perception of the whole simulated daylight environment after carrying out the vertical visual tasks. A five-level Likert scale was assigned for each question, with the most negative response scored as 1, and the positive response scored as 5. A total of 15 questions (see Table 6.4) were prepared and included variables that have a high possibility of being affected by lighting conditions with various colour temperatures. There included brightness, visual comfort (eye stain, headache, glare), naturalness, preciseness, uniformity, colour temperature, alertness, pleasantness and overall comfort [155, 174].

Part II (see Table 6.5) includes another 5 questions designed to estimate participants' visual perception after completing tasks that reviewed a sustained attention for approximately 5 minutes, and aimed to investigate the visual comfort and self-assessment of concentration levels.

Table 6.4: Questionnaire Part I: 15 questions for human perception of the luminous environment after completing the visual tasks on a vertical surface

	Questions	Bipolar descriptions
1	Whilst reading the chart, I found the brightness on the chart to be:	Insufficient--------------Sufficient
2	I felt glare whilst reading the chart:	Strongly disagree-Strongly agree
3	I had eye strain whilst reading the chart:	Strongly disagree-Strongly agree
4	I had a headache after reading the chart:	Strongly disagree-Strongly agree
5	How would you describe the colours in the chart?	Artificial- ------------------Natural
6	The coloured rings on the chart seem to be:	Blurry-----------------------Precise
7	I perceive the room as a whole to be:	Dark--------------------------Bright
8	How would you describe the light distribution in this room?	Uneven--------------------Uniform
9	How would you describe the feel of the lighting in the room:	Cool ------------------------- Warm
10	The lighting in the room makes me feel:	Sleepy-------------------------Alert
11	The lighting conditions in this room make me feel	Excited------------------------Calm
12	The lighting conditions in this room make me feel	Unpleasant----------------Pleasant
13	On a working day, I predict that I could work under these lighting conditions for	<1h; 1-3h; 4−5h；6-7h; >7h
14	Overall, I find the lighting conditions of this room to be	Uncomfortable------Comfortable
15	Do you think this lighting environment is appropriate for to conduct office work in?	Unacceptable---------Acceptable

Table 6.5: Questionnaire Part II: 5 questions for human perception after completing the horizontal tasks: d2 test of attention

	Questions	Bipolar descriptions
16	Whilst doing the ‘d2 test’, I found the brightness on the test sheet to be:	Insufficient-------------Sufficient
17	I felt glare whilst doing the ‘d2 test’:	strongly disagree-strongly agree
18	I had eye strain whilst doing the ‘d2 test’:	strongly disagree-strongly agree
19	I had a headache after doing the ‘d2 test’:	strongly disagree-strongly agree
20	How easy was it for you to concentrate when doing the ‘d2 test’:	Difficult – -------------------Easy

6.2.4. Procedures

Before the formal test, 5 participants were invited to complete a pilot test. Its purpose was to review the overall experimental procedures and refine these where improvements were identified. The results indicated that participants have the potential to be influenced by different colour temperatures when undertaking chromatic acuity and d2 test of attention. In the formal experiment, a total of 31 participants were invited to take part in this experiment, which was conducted during October of 2017. They are all postgraduate research students or staff working in the Energy Technologies Building between age of 20 and 45 (average age is 29.77, SD=5.69). This population comprised 18 males and 13 females, of whom 20 out of 31 made use of corrective lenses and none had colour vision deficiency.

All participants were required to finish five sessions with repeated steps. The duration of each session was approximately 10 minutes, and between every two sessions, a 5 minute break was provided in order to make sure the participants have sufficient relax and recovery. For each subject, the experiment commenced with a brief introduction to provide an overview of the process, and then general information about their recent history and experience was collected using questionnaires (see Appendix B). An example was used to demonstrate how to complete the d2 test, and following this each participant was asked to do a 3 practice trails to test their understanding of the process. The procedures for administrating the tests inside the mock-up office cell are listed below:

1. *Tell me directions of the gap in the Landolt rings one by one as fast and accurately as you can*
2. *Tell me the colours of the Landolt rings one by one as fast and accurately as you can*
3. *Finish the questionnaire Part I*
4. *Complete the as much of the d2 test as you can within the required duration*
5. *Finish the questionnaire Part II*
6. *Have a break / lighting condition changed by experimental investigator*
7. *Repeat steps 1, 2, 3, 4, 5*
8. *Repeat 6 and 7 four times*

According to previous research findings [215], learning effects and test-retest effects when repeating d2 test might obscure the influence of experimental variables. In order to reduce the effect of this error, the simulated daylit environment with the clear window was assigned to be the benchmark and was always the first lighting condition presented to subjects. The sequence of the other four thermochromic windows was randomly applied for the test with each participant. The test conducted with the clear window allowed subjects to develop familiarly precision and speed through completion of a full d2 test, and then combining this with randomization of window conditions, it is possible to reduce the learning effect. Because this experiment was primarily designed to evaluate the visual perception and sustained attention of participants working under the various thermochromic window conditions rather than the normal clear window, the use of the latter as a training exercise did not affect the outcomes.

6.3. Statistical analysis

In this experiment, the data collection from each participant includes: 1) error occurrence for the Chromatic acuity (CA) and colour naming (CN) tests repeated under five window conditions; 2) d2 test of attention answer sheet repeated under five window conditions; 3) answers to the questionnaire (Part I and Part II) repeated under five studied window conditions; 4) general demographic information and self-evaluation of temporal variables experienced prior to the test session. SPSS statistics 23 was used to complete the statistical analysis of the collected data.

6.3.1. Objective tasks

The simulated daylighting condition produced using the clear window was excluded from the analysis to reduce the error caused by learning effects. Although participants have been trained how to complete the d2 test prior to the formal tests, the data show that higher numbers of errors appeared to occur as compared with that for the thermochromic window as shown in Figure 6.3. Because of the 'practise makes perfect' effect associated with the d2 tests, the test carried out using the clear window was used as an opportunity for participants to gain practise in its completion. The errors for the clear glazing were probably caused by unfamiliarity with the d2 test, rather than the effects from the window condition. Thus, in the following analysis, the clear condition was excluded. In terms of data collected under the four TC window conditions, Friedman's ANOVA was used to detect whether the TC window conditions had an effect on participants' responses. The Wilcoxon signed-rank that was then applied as post hoc test to identify any of the specific differences caused by the different TC window conditions.

The non-parametric Friedman's ANOVA test was adopted, because the statistical inspection i.e., Kolmogorov-Smirnov (K-S) and Shapiro-Wilk (S-W), indicated that that assumption of normality of data distribution was violated, while the homogeneity of variance (Levene's test and modified Levene's test) was not violated [189, 192, 216]. The results from the K-S and S-W tests were presented in the Table 6.6. A p-value lower than 0.05 reveals that the difference between data distribution and normality is significant, i.e., assumption of normality of data distribution was violated. The results Table 6.6 indicate that the assumption of normality of data distribution for d2 test performance around the mean was violated ($p<0.05$). Therefore, it suggests that the alternative non-parametric ANOVA is a more appropriate method to analyse the data [217, 218].

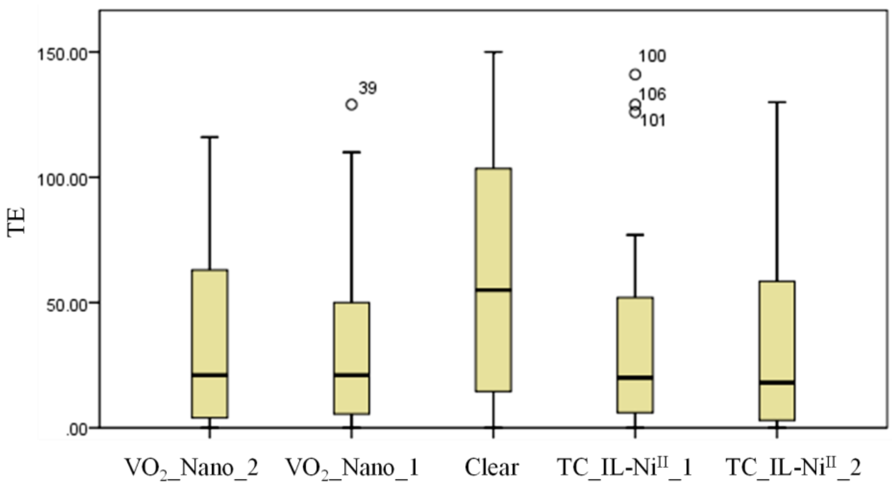


Figure 6.3: Boxplot of total error (TE) occurrence for d2 test under five lighting conditions respectively

Table 6.7 presents the results of non-parametric Levene's test, and modified Levene's test (also called Brown and Forsythe's test) of homogeneity of variance, including F test statistics, statistical significance (p-value) and effect size (η^2) for the difference. The results of both tests indicate that there are no statistically significant differences (p>0.05) for all cases of the d2 test across the variances of sampling distribution under each TC window condition. Eta-squared (η^2) was calculated to estimate effect size, and it is recommended that the strength of effect size is classified as small ($0.04 < \eta^2 \leq 0.25$), moderate ($0.25 < \eta^2 \leq 0.64$) and strong ($\eta^2 \geq 0.64$) [197]. It is noted that there is a small effect detected in the case of EC ($\eta^2 = 0.044$) in Levene's test (variance around mean), but the corresponding effect size in modified Levene's test (variance around median) is negligible [216]. Therefore, the assumption of homogeneity of variance was not violated.

Table 6.6: Results of the Kolmogorov-Smirnov and Shapiro-Wilk tests for performance in the d2 test of attention under four TC window conditions

		Kolmogorov-Smirnov			**Shapiro-Wilk**		
		Statistic	df	p-value	Statistic	df	p-value
EO	TC_U	0.182	31	0.01	0.822	31	0.00
	TC_S	0.190	31	0.01	0.832	31	0.00
	VO_2_U	0.164	31	0.03	0.850	31	0.00
	VO_2_S	0.204	31	0.00	0.837	31	0.00
EC	TC_U	0.539	31	0.00	0.176	31	0.00
	TC_S	0.530	31	0.00	0.340	31	0.00
	VO_2_U	0.514	31	0.00	0.321	31	0.00
	VO_2_S	0.537	31	0.00	0.270	31	0.00
CP	TC_U	0.181	31	0.01	0.824	31	0.00
	TC_S	0.164	31	0.03	0.853	31	0.00
	VO_2_U	0.191	31	0.01	0.833	31	0.00
	VO_2_S	0.205	31	0.00	0.836	31	0.00
TN	TC_U	0.313	31	0.00	0.591	31	0.00
	TC_S	0.335	31	0.00	0.616	31	0.00
	VO_2_U	0.299	31	0.00	0.601	31	0.00
	VO_2_S	0.285	31	0.00	0.680	31	0.00
PE	TC_U	0.215	31	0.00	0.748	31	0.00
	TC_S	0.207	31	0.00	0.800	31	0.00
	VO_2_U	0.194	31	0.00	0.781	31	0.00
	VO_2_S	0.228	31	0.00	0.817	31	0.00

Table 6.7: Homogeneity of variances within data distribution for performance in the d2 test of attention across the four TC window conditions

	Non-parametric Levene's test			**Brown and Forsythe's test**		
	F (3, 120)	p-value	Effect size ($\boldsymbol{\eta^2}$)	F (3, 120)	p-value	Effect size ($\boldsymbol{\eta^2}$)
EO	0.4	0.753	0.01	0.125	0.945	0.003
EC	1.826	0.146	0.044	0.290	0.832	0.007
CP	0.403	0.751	0.01	0.117	0.950	0.003
TN	0.314	0.815	0.008	0.033	0.992	0.001
PE	0.417	0.741	0.01	0.080	0.971	0.002

The results from the K-S and S-W tests carried out on the Chromatic Acuity (CA) and Colour Naming (CN) data are presented in Table 6.8. According to the data for error occurrence, the assumption of normality of the data distribution for all cases was violated ($p<0.05$). The results from the homogeneity of variances tests presented in Table 6.9 indicated that for data obtained from the CA test, the assumption of homogeneity of variance was not violated (i.e., $p>0.05$, $\eta^2 < 0.04$). However, for the CN test, the heterogeneity of variance was detected (i.e., $p<0.05, 0.04 < \eta^2 < 0.25$). Therefore, the following paired comparison associated with CN tests under different TC windows should be focused on the ranks (negative/positive) [219].

Table 6.8: Results for the Kolmogorov-Smirnov and Shapiro-Wilk tests for chromatic acuity (CA) and colour naming (CN) under four TC window conditions.

		Kolmogorov-Smirnov[a]			**Shapiro-Wilk**		
		Statistic	df	p-value	Statistic	df	p-value
CN	TC_U	0.278	31	0.000	0.754	31	0.000
	TC_S	0.401	31	0.000	0.661	31	0.000
	VO_2_U	0.302	31	0.000	0.759	31	0.000
	VO_2_S	0.244	31	0.000	0.842	31	0.000
CA	TC_U	0.270	30	0.000	0.762	30	0.000
	TC_S	0.257	30	0.000	0.757	30	0.000
	VO_2_U	0.275	30	0.000	0.700	30	0.000
	VO_2_S	0.335	30	0.000	0.686	30	0.000

Table 6.9. Homogeneity of variances within the data distribution for CA and CN tests across the four TC window conditions

	Non-parametric Levene's test			Brown and Forsythe's test		
	$F(3, 120)$	p-value	Effect size (η^2)	$F(3, 120)$	p-value	Effect size (η^2)
CN	7.281	0.000	0.154	4.848	0.003	0.108
CA	0.434	0.729	0.011	0.111	0.953	0.003

6.3.2. Subjective assessment

The subjective assessment using a 5-level Likert scale was repeated under the five window conditions for each participant. Unlike the objective tasks, subjective assessment would not be affected by human learning ability. Hence, the clear window condition was not excluded from this analysis. Non-parametric analysis is recommended, since the ordinal data based on ranks were obtained from Likert scale [199]. Meanwhile, the non-parametric Levene's test, and modified Levene's test indicated that the homogeneity of variance for all questions was detected not violated with the exception of question 10. Therefore, Friedman ANOVA and *post hoc* Wilcoxon signed rank were also appropriate for analysis of the answers of the subjective assessment.

6.4. Results and Analysis

6.4.1. Objective tasks

6.4.1.1. d2 test of attention

Table 6.10 illustrates the mean ranks, medians (M_{dn}), inter-quartile range (IQR), Test statistic (χ^2) and statistical significance (p-value) for the performance in d2 test of attention under the four TC window conditions, respectively. It can be seen that there is no statistically difference detected within the six parameters (EO, TE, EC, TN, CP, PE) for sustained attention under the four window conditions. For errors of omission (EO) and total error (TE), the distribution of medians, and mean ranks under the four different window conditions are almost the same. This means that error of commission (EC) as a part of TE has rarely occurred.

Table 6.10: Friedman test of performance about d2 test of attention

	Conditions	Mean Rank	M_{dn} (IQR)	χ^2	p-value
EO	VO_2_S	2.40	21(63)	0.417	0.937
	VO_2_U	2.60	21(45)		
	TC_U	2.47	20(47)		
	TC_S	2.53	18(58)		
EC	VO_2_S	2.48	0(0)	2.5	0.475
	VO_2_U	2.60	0(0)		
	TC_U	2.45	0(0)		
	TC_S	2.47	0(0)		
TE	VO_2_S	2.40	21(65)	0.417	0.937
	VO_2_U	2.60	21(47)		
	TC_U	2.47	20(47)		
	TC_S	2.53	18(58)		
TN	VO_2_S	2.52	653(39)	3.05	0.384
	VO_2_U	2.50	658(24)		
	TC_U	2.71	656(34)		
	TC_S	2.27	652(24)		
CP	VO_2_S	2.60	277(65)	0.417	0.937
	VO_2_U	2.40	277(47)		
	TC_U	2.53	278(47)		
	TC_S	2.47	280(58)		
PE	VO_2_S	2.40	0(0.099)	0.417	0.937
	VO_2_U	2.60	0(0.071)		
	TC_U	2.47	0(0.081)		
	TC_S	2.53	0(0.100)		

In terms of EO and TE, errors are similar under VO_2_S and VO_2_U conditions (M_{dn}=21), it decreases under the TC_U window condition (M_{dn}=20), and further decreases under the TC_S condition (M_{dn}=18). However, the differences were calculated as $\chi^2(3) = 0.417, p > 0.05$, revealing non-significance. This indicates that the scanning accuracy has rarely been influenced by the four TC window conditions. In terms of total number of characters processed (TN), the difference is not statistically significant as $\chi^2(3) = 3.05, p > 0.05$, which means that scanning speed was not affected under the different TC window conditions. Concentration performance (CP),$\chi^2(3) = 0.417, p > 0.05$, and percentage of error (PE) = TE / TN, $\chi^2(3) = 0.417, p > 0.05$, both reveal the non-significant difference.

Overall the results show that the various windows with colour temperatures of 3300K, 4000K, 6700K and 10000K at the illuminance level of 300lux on horizontal surface for the mock-up office have no effect on sustained attention for participants.

6.4.1.2. Chromatic acuity and colour discrimination

Table 6.11 presents the mean rank, median (M_{dn}), test statistic (χ^2) and statistical significance (p-value) for error occurrence in the colour acuity (AC) and colour naming (CN) tests under four TC windows. The Friedman test detected a the statistically significant difference in the results from the colour naming test (CN) test, $\chi^2(3) = 11.172, p = 0.011 < 0.05$. There was no significant difference detected in the for chromatic acuity test, $\chi^2(3) = 1.981, p > 0.05$. These results suggest that the four TC window conditions have no effect on the chromatic acuity. However, colour discrimination ability has the potential to be affected by TC windows conditions.

Table 6.11: Friedman test of error occurrence about chromatic acuity (CA) and colour naming (CN)

		Mean Rank	**M_{dn} (IQR)**	χ^2	**p-value**
CA	VO_2_S	2.48	0.0 (4)	1.981	0.576
	VO_2_U	2.70	1.0 (3)		
	TC_U	2.40	0.5 3.25)		
	TC_S	2.42	1.0 (3)		
CN	TC_U	2.45	1.0 (2)	11.172	0.011
	TC_S	2.06	0.0 (2)		
	VO_2_U	2.56	0.0 (1)		
	VO_2_S	2.92	1.0 (1)		

To isolate the main effect across the window conditions, a post hoc test by Wilcoxon signed-rank paired comparison was conducted. The effect size r (Pearson's correlation coefficient) was calculated as a supplement of null hypothesis significant test, which has the alpha level (0.05) as a significant criterion. Based on the suggestions from Ferguson [197], 0.2, 0.5 and 0.8 was taken as the lower bound of 'small', 'moderate' and 'large' effect size. Additionally, Bonferroni corrections were used to adjust the alpha level, aiming to reduce the increasing Type I error under the same hypothesis caused by multiple paired tests [201]. The corrected alpha level is 0.05/6=0.0083, which means that null hypothesis will be rejected when p-value is less than 0.0083. Table 6.12 shows the Wilcoxon signed-rank test results for the colour discrimination tasks. Six cases of pairwise comparisons were carried out in total across the four window conditions. Only 1 out of 6 cases was found to be significantly different from null hypothesis: the error occurrence for the CN task was significantly different between VO_2_S and TC_S conditions, with $Z=-3.433$, $p<0.0083$, $r=-0.436$ (small effect). In the prior inspection of data distribution for CN test, the homogeneity of variance was violated. Therefore, instead of comparing the difference between medians, it is more suitable to compare based on the signs of the ranks [219]. It can be seen that positive rank is the highest (positive =16, negative =2, ties=13) within error occurrence for CN test under VO_2_S against TC_S window conditions, which means that under VO_2_S window conditions, more participants made more colour discrimination mistakes. The remaining 5 pairwise comparisons show non-significant difference across the TC windows conditions ($p>0.0083$).

Table 6.12: Wilcoxon signed-rank pairwise comparison test with significant results of colour naming (CN)

Conditions (M_1 vs M_2)	M_{1dn} (IQR)	M_{2dn} (IQR)	p-value	Negative	Positive	Ties	Z	Effect Size (r)
TC_S vs TC_U	0 (1)	1 (1)	0.058	10	4	17	-1.895	-0.241
VO_2_U vs TC_U	0 (1)	1 (1)	0.155	8	9	14	-1.421	-0.180
VO_2_S vs TC_U	1 (2)	1 (1)	0.010	5	13	13	-2.588	-0.329
VO_2_U vs TC_S	0 (2)	0 (1)	0.015	5	12	14	-2.423	-0.308
VO_2_S vs TC_S	1 (2)	0 (1)	0.001*	2	16	13	-3.433	-0.436
VO_2_S vs VO_2_U	1 (2)	0 (2)	0.278	7	11	13	-1.086	-0.138

6.4.2. Questionnaires

6.4.2.1. Subjective assessment of the overall studied environment

The perceptions of participants were assessed by subjective rating using 15 questions after each of the CA and CN tasks. Use of Friedman test detected statistically significant differences across the five window conditions in 8 out of the 15 questions, as is shown in Table 6.13. This indicates that different types of windows have the potential to influence human perception of the following qualities:

1) The naturalness of chromatic visual tasks (Q5)

2) The brightness of the entire environment (Q7)

3) Impression of colour temperatures of the space (Q9)

4) Alertness (Q10)

5) Overall comfort involving pleasantness and tolerance (Q12, Q13, Q14 and Q15)

They all show statistically significant differences across the five window conditions ($p<0.05$).

For the remaining answers given to assess human perception of visual comfort (i.e. glare (Q2), eye stain (Q3), and headache (Q4)), lighting distribution and brightness, the

31 participants did not give significantly different responses ($p>0.05$) under the five window conditions. Overall, the Friedman test when applied to the answers to the 15 questions reveals that the different colour temperatures ranging from 3500 to 11000K could be discriminated under the illuminance of 350lux on a vertical surface. Meanwhile, statistically significant differences across TC window conditions were detected, when the overall levels of comfort was rated.

Table 6.13. Friedman test on responses to questions with significant results in questionnaire Part I

Questions	Conditions	Mean Rank	M_{dn} (IQR)	Mode	χ^2	p-value
Q5	Clear	3.02	3 (2)	2	18.41	0.001
	TC_U	2.97	2 (1)	2		
	VO_2_U	3.55	3 (2)	2		
	TC_S	2.16	2 (1)	2		
	VO_2_S	3.31	3 (2)	2		
Q7	Clear	3.84	4 (1)	3	21.43	0.000
	TC_U	3.11	3 (2)	3		
	VO_2_U	3.13	3 (1)	3		
	TC_S	2.37	2 (2)	2		
	VO_2_S	2.55	3 (1)	3		
Q9	Clear	2.76	2 (1)	2	13.12	0.011
	TC_U	2.06	2 (1)	2		
	VO_2_U	4.08	3 (1)	4		
	TC_S	1.5	1 (1)	1		
	VO_2_S	4.6	4 (0)	4		
Q10	Clear	2.94	3 (1)	3	13.12	0.011
	TC_U	3.53	3 (2)	4		
	VO_2_U	3.19	3 (1)	3		
	TC_S	2.97	3 (2)	3		
	VO_2_S	2.37	3 (1)	2		
Q12	Clear	2.9	3 (0)	3	30.62	0.000
	TC_U	2.76	3 (1)	3		
	VO_2_U	3.71	3 (1)	3		
	TC_S	2.11	2 (1)	2		
	VO_2_S	3.52	3 (1)	3		
Q13	Clear	3.1	3 (1)	2	20.18	0.000
	TC_U	2.92	2 (1)	2		
	VO_2_U	3.68	3 (2)	2		
	TC_S	2.16	2 (2)	1		
	VO_2_S	3.15	3 (2)	2		
Q14	Clear	2.92	3 (2)	2	30.19	0.000
	TC_U	2.97	3 (2)	2		
	VO_2_U	3.9	4 (1)	4		
	TC_S	1.97	2 (1)	2		
	VO_2_S	3.24	3 (2)	3		
Q15	Clear	3.27	3 (2)	2	25.36	0.000
	TC_U	3.13	3 (2)	2		
	VO_2_U	3.69	4 (1)	4		
	TC_S	1.97	2 (2)	2		
	VO_2_S	2.94	3 (2)	2		

Wilcoxon signed-rank pairwise comparisons were conducted to investigate window conditions eliciting the different responses of participants [220]. Considering multiple pairwise comparison within the same hypothesis (i.e., in total 10 pairs of comparison for each question under the five window conditions), the error rate was found to be 0.4, i.e., the probability of making at least one Type I error is 40%. To counter this, Bonferroni corrections was applied to control Type I errors (i.e., rejection of the null hypothesis when it is true), with the alpha level for identifying a significant criterion calculated as 0.005. In addition, effect size (r) was calculated to show the magnitude of the difference between independent variables. Table 6.14 shows medians, negative, positive and ties ranks against the hypothesis, statistical significance (p-value), statistic Z value, and effect size (r) of the pairwise comparisons with significant results. Some of the pairwise comparisons did not meet the requirement of Bonferroni corrected statistical significance (i.e., $p<0.005$), however, their effect size (r) was notable, which fell into the 'small' range (i.e., $0.2<r<0.5$). This means that increasing the sample size has the potential to yield significant results [193, 202]. Therefore, the results with non-significant p-value by notable effect size were considered to avoid the Type II error (i.e., failure to reject the null hypothesis when it is false).

In terms of colour rendition (i.e., Q5 about naturalness), it can be seen that, 3 out of the 10 pairwise comparisons were detected as significantly different from null hypothesis ($p<0.005$), with the effect sizes falling into the 'small' range ($0.2<r<0.5$). It can be seen that median rating for the TC_S (M_{dn}=2) window condition is lower than that of the Clear (M_{dn}=3), VO_2_U (M_{dn}=3), and VO_2_S (M_{dn}=3) window conditions. There is a small effect (r= -0.341) but non-significant (p=0.007, >0.005) difference, for the comparison of the TC_S with the TC_U window condition and this dominated the negative ranks. This indicates that the TC_S window was considered to be more artificial than the TC_U window condition. The results indicated that TC_S window leads to relatively greater perception of an artificial colour rendering than the other four conditions. However, participants did not detect any significantly difference between the Clear, VO_2_U, TC_U and VO_2_S window conditions in their ability to render colour in a natural manner.

In terms of the sensation of brightness (Q7), 1 out of 10 cases was found to be statistically significant ($p<0.005$) for the difference between assigned two variables, i.e. VO_2_U and Clear. Another 4 out of the 10 cases present differences based on their effect sizes (i.e., falling in the small range $0.2<r<0.5$), even if their statistical significances cannot achieve the Bonferroni corrected p-value (i.e., $0.005<p<0.05$). The medians of the responses to Q7 under the Clear window condition have higher ratings than that for other four conditions. A high negative rank indicates that the Clear window condition has more positive answers within every pairwise comparison. This also provides evidence to indicate that the clear window providing daylighting with a CCT of around 5000K is perceived as brighter than the tinted TC window conditions, under the illuminance level of 350 lux. In addition, responses under TC_S window condition ($M_{dn}=2$) have a lower median and a high negative rank when compared with that of TC_U ($M_{dn}=3$). This indicates that the TC_S window condition was perceived as less bright than the TC_U condition.

Q9 explains the perception of colour temperature qualified on a scale between cool and warm. From the results, 9 cases out of 10 pairwise comparisons show statistically significant ($p<0.005$) differences across the five window conditions, with the effect sizes mostly falling into the moderate range ($0.5<r<0.8$, 5 cases out of 10), or the ‘small’ range ($0.2<r<0.5$, 4 cases out of 10). The remaining 1 case failed to achieve the required significance ($p=0.027>0.005$), however the effect size ($0.2<r<0.5$) indicates a notable difference as well. According to the median and ranks (negative or positive against hypothesis), the inferential correlations are: TC_S< TC_U < Clear< VO_2_U < VO_2_S, where '<' means that former window condition has a lower median and rank, i.e., feels cooler than the latter one. The results are consistent with the measured CCTs, indicating that participants could accurately tell the difference between the environmental colour temperatures ranging across 3500K to 11000K.

Assessment of alertness was measured by Q10, however, according to violated homogeneity of variance test of data distribution of Q10, the comparison was recommended to be focused on signs of ranks (i.e., negative, positive, and ties). A Wilcoxon signed-rank test did not detect any significant difference ($p<0.005$), but the results shown in Table 6.14 have a p-value less than 0.05. It can be seen that medians of responses to Q10 under TC_U, VO_2_U, TC_S and VO_2_S are all the same as score of 3, however, the number of negative ranks against the hypothesis reveal that the TC_U condition induces higher alertness than TC_S and VO_2_S, while the VO_2_U condition induces greater alertness than the VO_2_S condition. This indicates that VO_2_S window conditions result in less alertness than both the VO_2_U and TC_U windows, and that the TC_S window potentially leads to less alertness than the TC_U condition.

Different aspects of overall assessment of the five lighting conditions were evaluated through questions 12, 13, 14, and 15, which explored pleasantness, predicted tolerance duration, acceptance and comfort for work. Pleasantness was rated by Q 12, and 3 out of the 10 cases were detected to exhibit a statistically significant difference ($p<0.005$) from the null hypothesis. The results indicate that the Clear ($M_{dn}=3$), VO_2_U ($M_{dn}=3$) and VO_2_S ($M_{dn}=3$) window conditions can lead to a luminous environment that is perceived as more pleasant than TC_S ($M_{dn}=2$). Moreover, 5 out of the 10 cases have notable differences based on their substantive effect sizes, i.e., $0.005<p<0.05$, and $0.2<r<0.5$. Ranks reveal that the VO_2_S and VO_2_U window conditions have greater potential to avoid an unpleasant luminous environment than the TC_U and Clear windows, and compared with the TC_S condition, the TC_U condition is preferred.

The self-assessment of how long subjects felt they could tolerate working under the five window condition were reported through Q13. The results reveal two statistically significant cases ($p<0.005$) and dominated negative ranks, i.e., TC_S vs TC_U; TC_S vs VO_2_U, indicate that people would like to spend more time under the TC_U (M_{dn}=2) and VO_2_U (M_{dn}=3) window condition rather than under the TC_S (M_{dn}=2) condition. The remaining 3 cases have notable differences based on effect sizes ($0.2<r<0.5$), indicating that the VO_2_U window condition potentially was given a higher rating than the VO_2_S window, and that the VO_2_S and TC_U window conditions were respectively rated more positively than the TC_S window condition.

For Q14, which explained subjects willingness to work under the studied luminous environments, it can be seen that 6 out of the 10 cases were detected as significant different ($p<0.005$) from the null hypothesis. The results indicate that the TC_S (M_{dn}=2) window condition obtained a lower rating than the VO_2_U (M_{dn}=4), VO_2_S (M_{dn}=3), TC_U (M_{dn}=4), and Clear (M_{dn}=3) window conditions. Moreover, it is noted that the VO_2_U window condition was significantly more acceptable than Clear (M_{dn}=3) and VO_2_S (M_{dn}=3) window conditions.

Q15 relating to comfort level also has similar tendency to Q14. The luminous environment created by the window TC_S (M_{dn}=2) was reported as being less comfortable than the TC_U (M_{dn}=3), Clear (M_{dn}=4), and VO_2_U (M_{dn}=4) windows, with a difference that is statistically significant ($p<0.005$, $0.2<r<0.5$). Meanwhile, small effect size and sign of ranks indicated that the VO_2_U (M_{dn}=4) window is possibly better than the VO_2_S (M_{dn}=3) window (i.e., $0.005<p<0.05$, r=0.330), and that the VO_2_S has the potential to be more comfortable than the TC_S (M_{dn}=2) window condition.

Table 6.14: Wilcoxon signed-rank test of responses to questions in questionnaire Part I with significant results produced under five studied lighting conditions

Questions	Hypothesis (M1 vs M2)	M_{1dn}	M_{2dn}	p-value	Negative	Positive	ties	Z	Effect Size (r)
Q5	TC_S vs Clear	2	3	0.004*	17	5	9	-2.910	-0.370
	TC_S vs TC_U	2	2	0.007	14	4	13	-2.686	-0.341
	TC_S vs VO_2_U	2	3	0.001*	20	3	8	-3.217	-0.409
	VO_2_S vs TC_S	3	2	0.002*	3	16	12	-3.159	-0.401
Q7	VO_2_U vs Clear	3	4	0.001*	20	3	8	-2.288	-0.291
	VO_2_S vs Clear	3	4	0.006	18	3	10	-2.287	-0.290
	TC_U vs Clear	3	4	0.022	14	4	13	-3.318	-0.421
	VO_2_U vs Clear	3	4	0.022	13	3	15	-2.748	-0.349
	TC_S vs TC_U	2	3	0.030	16	5	10	-2.164	-0.275
Q9	TC_U vs Clear	2	2	0.027	17	5	9	-2.215	-0.281
	VO_2_U vs Clear	3	2	0.000*	0	22	9	-4.193	-0.533
	TC_S vs Clear	1	2	0.000*	25	4	2	-3.906	-0.496
	VO_2_S vs Clear	4	2	0.000*	0	26	5	-4.517	-0.574
	VO_2_U vs TC_U	3	2	0.000*	0	28	3	-4.697	-0.597
	TC_S vs TC_U	1	2	0.003*	12	1	18	-3.000	-0.381
	VO_2_S vs TC_U	4	2	0.000*	1	30	0	-4.853	-0.616
	TC_S vs VO_2_U	1	3	0.000*	31	0	0	-4.934	-0.627
	VO_2_S vs VO_2_U	4	3	0.001*	2	16	13	-3.252	-0.413
	VO_2_S vs TC_S	4	1	0.000*	0	30	1	-4.871	-0.619
Q10	TC_S vs TC_U	3	3	0.038	8	2	21	-2.070	-0.263
	VO_2_S vs TC_U	3	3	0.009	18	4	9	-2.628	-0.334
	VO_2_S vs VO_2_U	3	3	0.011	14	2	15	-2.540	-0.323
Q12	TC_S vs VO_2_U	2	3	0.000*	20	2	9	-3.765	-0.478
	VO_2_S vs TC_S	3	2	0.001*	4	18	9	-3.286	-0.417
	TC_S vs Clear	2	3	0.003*	16	3	12	-2.982	-0.379
	VO_2_S vs Clear	3	3	0.036	4	13	14	-2.101	-0.267
	VO_2_U vs TC_U	3	3	0.006	2	15	14	-2.751	-0.349
	TC_S vs TC_U	2	3	0.037	14	4	13	-2.082	-0.264
	VO_2_S vs TC_U	3	3	0.033	4	14	13	-2.130	-0.271
	VO_2_U vs Clear	3	3	0.010	2	14	15	-2.588	-0.329
Q13	TC_S vs TC_U	2	2	0.002*	15	2	14	-3.13	-0.398
	TC_S vs VO_2_U	2	3	0.003*	12	5	5	-2.983	-0.379
	VO_2_S vs VO_2_U	3	3	0.029	9	2	20	-2.179	-0.277
	VO_2_S vs TC_S	3	2	0.027	6	16	9	-2.217	-0.282
	TC_S vs Clear	2	3	0.009	16	3	12	-2.622	-0.333
Q14	VO_2_U vs Clear	4	3	0.005*	5	18	8	-2.811	-0.357
	TC_S vs Clear	2	3	0.004*	17	3	11	-2.899	-0.368
	TC_S vs TC_U	2	3	0.003*	16	2	13	-2.982	-0.379
	TC_S vs VO_2_U	2	4	0.000*	24	3	4	-4.139	-0.526
	VO_2_S vs VO_2_U	3	4	0.003*	16	3	12	-3.013	-0.383
	VO_2_S vs TC_S	3	2	0.005*	5	20	6	-2.819	-0.358
Q15	TC_S vs Clear	2	3	0.001*	20	4	7	-3.312	-0.421
	TC_S vs TC_U	2	3	0.000*	20	1	10	-3.908	-0.496
	TC_S vs VO_2_U	2	4	0.000*	23	5	3	-3.741	-0.475
	VO_2_S vs VO_2_U	3	4	0.009	15	3	13	-2.6	-0.330
	VO_2_S vs TC_S	3	2	0.014	7	18	6	-2.455	-0.312

*** Statistically significant different**

6.4.2.2. Subjective assessment of the horizontal workplace

Questionnaire Part II consisted of 5 questions and was administered following the d2 test of attention. It aimed to investigate participants' perceptions after having to sustain short periods of concentration under the five different window conditions. Table 6.15 reports the results of the Friedman test for the responses to the questions, which indicated that and 2 out of the 5 questions exhibited significant differences across the five window conditions. They were calculated as follows:

1) Brightness levels, $\chi^2(4) = 11.523, p < 0.05$,

2) Self-assessment of the concentration levels: $\chi^2(4) = 19.481, p < 0.05$.

Table 6.15: Friedman test of responses to questions with significant results in questionnaire part II

	Conditions	Mean Rank	M_{dn} (IQR)	Mode	χ^2	p-value
Q16	Clear	3.29	3 (1)	3	11.523	0.021
	TC_U	3.32	3 (2)	3		
	VO_2_U	3.21	3 (1)	3		
	TC_S	2.42	3 (2)	2		
	VO_2_S	2.76	3 (2)	2		
Q20	Clear	2.55	3 (2)	3	19.481	0.001
	TC_U	3.31	4 (1)	4		
	VO_2_U	3.45	3 (1)	3		
	TC_S	2.31	3 (2)	2		
	VO_2_S	3.39	4 (1)	4		

For the other three questions which explored the effects of visual comfort on eye strain, headache, and glare, no statistically significant differences were detected across the five window conditions. This means that under an illuminance of 300lux on a horizontal workplane, changing colour temperatures between 3000K and 10000K did not have an effect on visual discomfort.

Wilcoxon signed-ranks tests were conducted to explore the main effect variables based on the results of the Friedman test. A total of 10 comparisons were carried out for each question, and the significant results under the five window conditions are shown in Table 6.16. Bonferroni corrected alpha level of 0.005 was applied.

No statistically significant differences (i.e., $p>0.005$) were detected in the 10 pairwise comparisons of Q16. However, regarding the effect sizes ($0.2<r<0.5$), 2 out of the 10 cases have notable differences. The comparison of the TC_S against the TC_U window condition, yielded dominated negative ranks, which indicated that the TC_U window condition was considered to provide a level of brightness that was more sufficient than the TC_S window condition. The VO_2_U also received higher ranks than the TC_S window condition.

In terms of concentration assessment (Q20), 4 out of the 10 paired comparisons showed statistically significant ($p<0.005$) differences from the null hypothesis. Regarding both median difference and sign of ranks, the TC_S window condition ($M_{dn}=3$) was given a lower rating than the TC_U ($M_{dn}=4$), VO_2_U ($M_{dn}=3$) and VO_2_S ($M_{dn}=4$) window conditions respectively. In addition, the VO_2_U window condition ($M_{dn}=3$) was considered more conducive to concentration than the Clear window condition ($M_{dn}=3$), i.e., negative ranks dominated when comparing the VO_2_U window against the Clear window. Another case ($0.005<p<0.05$) failed to achieve the required significance but the notable difference was detected by the 'small' effect size ($0.2<r<0.5$). Dominated positive ranks between the comparison of the VO_2_S ($M_{dn}=4$) against the Clear window condition ($M_{dn}=3$), reveal that the VO_2_S window is more conducive to enables more concentration.

Table 6.16: Wilcoxon signed-rank test of responses to questions in questionnaire Part II with significant results produced under the five studied lighting conditions

Questions	Hypothesis (M_1 vs M_2)	M_{1dn}	M_{2dn}	p-value	Negative	Positive	Ties	Z	Effect Size (r)
Q16	TC_S vs TC_U	3	3	0.009	16	3	12	-2.622	-0.333
	TC_S vs VO_2_U	3	3	0.052	15	7	9	-1.941	-0.247
	VO_2_U vs Clear	3	3	0.004*	3	15	13	-2.853	-0.362
	VO_2_S vs Clear	4	3	0.018	6	18	7	-2.373	-0.301
	TC_S vs TC_U	3	4	0.000*	16	1	14	-3.578	-0.454
Q20	TC_S vs VO_2_U	3	3	0.003*	17	4	10	-2.992	-0.380
	VO_2_S vs TC_S	4	3	0.003*	4	15	12	-2.941	-0.374

*** Statistically significant different**

According to the scheduling of questionnaires: questions 1-4 seek to evaluate brightness and visual comfort following completion of the vertical tasks; while questions 16-19 assesses the same qualities after completion of the horizontal tasks. Wilcoxon signed-rank comparisons between the corresponding questions, i.e. Q1 vs Q16, Q2 vs Q17, Q3 vs Q18, and Q4 vs Q19 were conducted, and the significance of the results is shown in Table 6.17. An alpha level of 0.05 was applied as the significance criteria. The results indicate that, under the TC_U and TC_S window conditions, the difference between answers to Q4 and Q19 were statistically significant ($p<0.05$). Effect sizes (r) also reported notable differences as a ‘small’ effect ($0.2<r<0.5$). The negative ranks of difference between Q4 and Q19 under both the TC_U and TC_S window conditions indicate that Q19 received stronger agreement indicating that subjects were more inclined to report the feeling of having a headache. The results indicate that there is relatively more chance of getting headache sensation when undertaking horizontal tasks in the working environment with the TC_U or TC_S windows.

Table 6.17: Wilcoxon signed-rank test of responses to questions with significant results within the comparison between assessment about vertical and horizontal tasks

Window conditions	Conditions (M_1-M_2)	M_{1dn}	M_{2dn}	p-value	Negative	Positive	Ties	Z	Effect Size (r)
TC_U	Q4 vs Q19	2	2	0.046	6	1	24	-1.994	-0.253
TC_S	Q4 vs Q19	2	2	0.034	7	1	23	-2.121	-0.269

6.5. Summary and discussion

6.5.1. Objective and subjective assessment of sustained attention

Sustained attention (i.e., concentration) was measured by using the d2 test of attention, supported thought self-assessment of participant's concentration. The d2 test results show that no significant difference, especially of scanning accuracy (i.e., EO, EC, PE) and speed (i.e., TN), was detected under the four TC window conditions. This suggests that in the test environment with illuminance levels of around 300lux, the tinted conditions with CCTs of 3300K, 4000K, 7000K and 11000K have no effect on sustained attention. This result was not consistent with previous findings that indicate intermediate (e.g. 4300K) or slightly cold (e.g. 6500K) lighting conditions can lead to higher levels of concentration than lighting condition that sit above and below these conditions on the Planckian locus (i.e., 2900K warm and 12000K cold) [208, 209]. However, subjective estimation of concentration indicated that the VO_2_U (CCT=3300K) and VO_2_S (CCT=4000K) window conditions supported concentration more effectively than the Clear window conditions (CCT=5000K), but the TC_S (CCT=11000K) window condition led to a decrease in concentration. The results from the subjective assessment were similar to previous findings [208, 209].

Studies exploring the effectiveness of the d2 test of attention indicate that, the performance in the d2 test is highly related to the level of education, i.e. subjects with higher education maintain a relatively higher scanning speed and lower error occurrence throughout the trails of the d2 test [221]. In this study, participants are all working or studying in Energy Technologies Building, and educated at postgraduate level. This has the potential to explain why objective tasks did not present significant difference. Although subjects perceived the condition as making it relatively difficult to concentrate on tasks performed under the TC_S window condition, they were also able to maintain attention. The d2 test only measured the sustained attention (short-term), thus whether the studied TC window conditions would affect concentration levels. During long-term working would require a further experiment, such as the threshold of time spent continuously on work.

6.5.2. Chromatic visual performance

The CA test did not present significant difference across the four TC window conditions, and around 50% of subjects made no errors on achromatic acuity test. This suggests that different CCT have no effect on acuity as measured by this test under an illuminance of 300lux. As shown in Table 6.2, during the CA and CN test which involved observation of chromatic Landolt rings, the luminance measured from the location of the participants' eyes was over 25 cd/m^2. For the human visual system, spectral sensitivity changes at different retinal illuminance. That leads to different combined operation of photoreceptors, with three states of sensitivity being identified as photopic vision (luminance> 5 cd/m^2), scotopic vision (luminance < 0.005 cd/m^2), and mesopic vision (0.005 cd/m^2 < luminance < 5 cd/m^2) [133]. Luminance in this study is higher than 5 cd/m^2, falling into the state of photopic vision, which means that both colour vision and fine resolution of detail can be available.

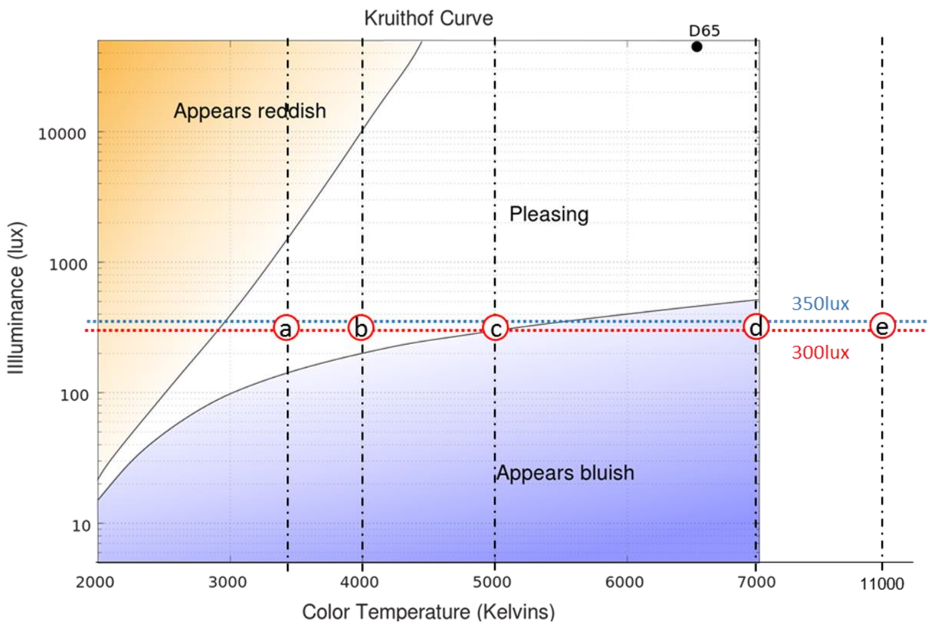
However, the CN test presented a significant difference between the VO_2_S and TC_S window conditions. Thus it is possible that the VO_2_S window might lead to more errors. Two issues should be considered to explain this result: 1) Error occurrence in the CA test has relationship with that of CN, Spearman's rho (ρ) was applied to measure the relationship a between CA and CN result, concluding that under the VO_2_U (ρ=0.561, p=0.001, <0.05) and VO_2_S (ρ=0.504, p=0.004, <0.05) window conditions, CA shows a significant positive relationship with CN [197]; 2) CCT under different TC window conditions may have affected colour discrimination. Since the results of the CN test violated the homogeneity of variance, Wilcoxon paired comparison became less powerful at detecting the difference. Thus, further studies with a constant size of achromatic letters and larger sample size are proposed to learn more about the main effects.

6.5.3. Perception of luminous environment produced by chromatic windows

According to the assessment reported through the repeated measures questionnaire under the five window conditions, it was found that the ranking of perceived coolth or warmth of the luminous environment was consistent with the CCT of the five window conditions which ranged from 11000K to 3300K. This indicates that under the levels of illuminance used in these tests (around 300lux), subjects could accurately identify the sensations appropriate to the CCT of the window conditions

The Clear window condition was judged by subjects to be the brightest, which means that, under the same levels of illumination, 5000K was perceived brighter than lower (3300K and 4000K) and higher (7000K and 11000K) CCTs. The brightness was also perceived to drop when moving from 11000K source to 7000K source. Previous studies exploring the relationship between brightness and CCT have mostly focused on CCTs ranging between 2900 and 8000K. Thus, the results here that up to 5000K increasing CCT yields a brighter luminance environment is partially consistent with previous findings that higher CCTs lead to the perception increased brightness [21, 144, 222, 223]. Other studies indicated that higher CCT might not appear brighter, which matches the results obtained here for sources above 5000K, suggesting there is not a linear relationship between CCT and brightness [224, 225].

The relative reddish/warm condition caused by the VO_2_S (3300K) source received a greater number of negative responses in relation to alertness, when compared with the TC_U (7000K) and VO_2_U (4000K) window conditions. Additionally, the TC_S window induced less alertness than the TC_U condition, although the difference is not statistically strong. This result is consistent with studies that increasing CCT can improve alertness level [152, 210], and again indicate that there may be an optional CCT after which the effect reverses.



	a	b	c	d	e
Windows	VO_2_S	VO_2_U	Clear	TC_U	TC_S
CCT (K)	3300	4000	5000	7000	11000

Figure 6.4. The human impression of CCTs in five studied lighting conditions respectively when the illuminance is between 300-350lux (Kruithof curve, modern version, source: https://en.wikipedia.org/wiki/Kruithof_curve , modified by author)

It was found that participants prefer the warm tinted conditions, such as the two VO_2_Nano window conditions, to those provided by cool tinted conditions, especially in terms of pleasantness. This result is consistent with the Kruithof curve shown in Figure 6.4, over which the CCT of each window condition has been plotted [178, 212]. It can be seen that, the CCT of the VO_2_U and VO_2_S lie within the pleasing area when illuminance level is between 300 and 350lux. The TC_U and TC_S window conditions fall into the region where sources are perceived as bluish and where discomfort might be experienced.

TC_S window, which is the most bluish/cool one of the conditions used in this experiment, was perceived as being the most artificial of the five conditions when observing the coloured Landolt rings. In addition, the findings indicate that working on different tasks under cool tinted conditions (i.e., the TC_U or TC_S window conditions) results in a higher probability of subjects reporting headache symptoms. Most of the participants predicted that they could spend between 4-5 hours under the VO_2_U window condition, which was the longest of all the window conditions. Subjects reported that the TC_S window condition as the one they would want to spend the least time in with the majority indicates less than 1 hour. To sum up, under the 300lux illuminance level, the most comfortable and acceptable window condition was found to be that produced by the VO_2_U window with a CCT of 4000K, whereas, the TC_S window condition with CCT of 11000K was deemed to be the most uncomfortable one. Previous studies also gave rise to similar findings suggesting that warm lighting with a CCT of around 3500K is beneficial for visual comfort [21, 153].

6.5.4. Summary

Overall the findings in this study indicated that, during the development of TC glazing for building application, it is important to consider human visual performance and subjective perception if the tinted light they admit into a space. In terms of blue/cool tinted TC windows, increasing the degree of tint from light to dark blue might cause visual discomforts such as unnaturalness of visual targets, and unpleasantness in the mood. It was found that brown/warm tinted TC windows are more acceptable than windows with a blue tint. This means that brown/warm tinted TC materials could increase the degree of tint to be darker brown/warmer, enlarging the adjustment of admitting daylight into the buildings.

Chapter 7

Conclusions and Future Work

Thermochromic (TC) smart windows enable reversible and dynamic adjustment of the transmitted solar radiation depending on temperature variations. VO_2 based films, as the most widely studied materials for TC windows, have the feature of reducing NIR transmittance on hot days to reduce indoor solar heat gain, therefore, saving cooling energy consumption. However, various studies in the field focused on the improvement of VO_2 materials at lab stage and only a few concerned about their performance on buildings. Then, aims of this study are to conduct a comprehensive analysis of the TC window performance and provide suggestions to develop TC windows for practical building requirement.

Both numerical simulation by EnergyPlus and laboratory controlled experiments were carried out in this study, predicting energy consumption and visual comfort affected by tinted thermochromic windows applied in buildings. This section concludes the findings from simulation and experimental studies. Additionally, the limitations of this study were discussed, and further works were suggested.

7.1. Conclusions from the effects of selected thermochromic windows on building performances

Comprehensive analysis of five types of well-developed thermochromic windows with different transition temperatures and optical properties were investigated under five representative climatic conditions in China. A series of simulation has been conducted to explore the main factors that cause the thermochromic transition of TC windows, and further affect the energy and daylighting performance. Moreover, the window sizes and climates that are appropriate to be used for each of the five selected TC windows were summarised.

The following conclusions can be drawn: 1) Lowering transition temperature may yield undesirable tinted hours on cold days, leading to increase heating energy consumption. Enlarging the change of solar transmittance has the potential to be relatively more efficient to attain desirable thermochromic performance. 2) TC windows with relatively lower absorptance and higher transition temperatures such as VO_2_t38 and NVO_2_t40 required higher ambient temperature and solar radiation to trigger the transition. 3) The thermochromic glazing mainly provides energy saving by reducing the cooling demand of the building. Thus, the severe cold zone in China, where heating consumption dominated, would not be an appropriate climatic condition to use TC windows. A relatively higher visible transmittance could contribute to energy efficiency by reducing artificial lighting demand. 4) All types of thermochromic glazing were shown, leading to an increase of desired annual daylight hours within $UDI_{500\text{-}2000lux}$, in the region near the window by reducing oversupplied daylighting ($UDI_{<2000lux}$). Increasing solar altitudes of the city enlarged the negative effect of TC windows on $UDI_{500\text{-}2000lux}$ in the region far from the window 5) The appropriate window-to-wall ratio for using a particular TC window was explored, resulting in more energy efficiency when applying TC glazing in a larger window. Also, it was found that most types of TC glazing had the potential to achieve the balance of both energy saving and desirable daylighting simultaneously, in Hangzhou, Kunming and Guangzhou. However, there are limited types of TC glazing achieving that balance under colder climates such as that of Beijing and Harbin.

7.2. Conclusions from the thermochromic windows on oversupplied daylighting control and optimisation of building energy consumption

A follow-up study was carried out to further explore the potential development of TC glazing for visible light control. Different from VO_2 based TC materials (e.g.,

VO_2_Nano), a TC material with tunable visible transmittance (e.g., TC_IL-Ni^{II}) was employed to achieve dynamic daylight control. Different scenarios were conducted to optimize TC window performance through varying the transition temperature of the selected TCs, improving the visible and NIR transmittance, and combination of different TC window films. Energy efficient and desired daylighting affected by different TC scenarios were discussed under the climatic conditions of Beijing, Shanghai and Guangzhou.

Conclusions were obtained as follows: 1) each of the selected TCs has its proper transition temperatures depending on different climates. For VO_2_Nano windows, the proper transition temperatures are higher than the room temperature, which is between 30-35°C. While a transition temperature of 20°C or less is appropriate for the TC_IL-Ni^{II} windows to achieve the more energy saving; 2) using the VO_2_Nano or TC_IL-Ni^{II} window individually is effective to reduce the oversupplied daylighting in the region near the window, however, the high visible transmittance (i.e., 0.97-0.79) of TC_IL-Ni^{II} film at clear state leads to a restricted capacity of reducing daylight transmitted; 3) enlarging the reduction of NIR transmittance for VO_2_Nano and visible transmittance for TC_IL-Ni^{II}, respectively, can improve the building energy efficiency. Meanwhile, the optimal transition temperatures of the improved VO_2_Nano and TC_IL-Ni^{II} windows are not changed in Beijing and Shanghai. However, in Guangzhou, the proper transition temperature of VO_2_Nano decreases (i.e., 20°C) when the NIR transmittance has further reduction at tinted state, while that of TC_IL-Ni^{II} window increases with a lower visible transmittance at tinted state; 4) the improved TC_IL-Ni^{II} window has a better performance in terms of daylighting adjustment, but still less efficient than VO_2_Nano because of its high visible transmittance at clear state; 5) cooperation of TC_IL-Ni^{II} and VO_2_Nano films led to further improvement of both energy and daylighting performance.

Depending on climatic characteristics, 'VIS_30 NIR_40' is the best case in Beijing (i.e., reducing the glaring risk on cold days, and both glare and overheat on hot days). 'NIR_40 VIS_30' is the best case for Guangzhou (i.e., reducing glare and overheat on hot days, and keep sufficient daylighting on warm days). Both of the improved VO_2_Nano working individually and 'VIS_30 NIR_40' could result in better energy and daylighting performance, under the moderate warm climate of Shanghai.

7.3. Conclusions from lab investigation about human response to TC tinted window applied in the working environment.

TC windows not only affect the energy and luminous environment inside a building but also have a capacity of tinting to different colours after the transition. Therefore, the change of CCT due to the TC glazing might impact on both the visual perception of the indoor environment as well as the personal psychologically sensations of the occupants. In Chapter 5, an innovative test room cubicle lit by an artificial window was designed to investigate whether different TC glazing containing different colours can influence the visual responses given by test participants. Especially, the study aims to investigate the visual responses when carrying out both objective tasks (i.e., achromatic acuity, chromatic acuity and colour naming) and subjective assessment. Under a low illuminance level of 100lux, 31 participants were recruited to take repeated measures test and survey in a test room with three window configurations simulating VO_2_Nano (4000K), TC_IL-Ni^{II} (7000K), and reference Clear (5000K) windows, respectively.

The findings showed that achromatic acuity was reduced under VO_2_Nano window condition compared with the other two under the low illuminance levels. Moreover, time spent measurements indicated the TC_IL-Ni^{II} window condition was beneficial to keep efficiency for work. However, chromatic acuity and colour naming tests had no significant differences across the three window conditions. The subjective assessment indicated that participants preferred to stay and work under both VO_2_Nano window. TC_IL-Ni^{II} window was considered to cause unnatural sight, and relatively uncomfortable.

7.4. Conclusions from lab investigation on human visual performance and sustained attention affected by potential TC tinted window

The experiment in Chapter 5 was based on threshold and supra-threshold method with a low illuminance level of 100lux, and most of the negative responses were given due to insufficient brightness. Therefore, Chapter 6 investigated five window conditions (i.e., adding further tinted TC_IL-Ni^{II} (11000K) and VO_2_Nano (3300K)) under a comfort illuminance level of 350 lux. This study aims to further understand the effect of tinted TC windows on visual performance (i.e., achromatic acuity, colour naming), sustained attention (i.e., a d2 test of attention) and subjective sensations, in addition, switched state of the TC windows were also investigated.

The statistical analysis presents that no significant difference was detected in chromatic acuity and sustained attention test. Subjective assessment in this study indicated that for blue/cool tinted TC_IL-Ni^{II} windows, further tinting to dark blue might cause visual discomforts such as unnaturalness of visual targets, unpleasantness in the mood. While regarding brown/ warm tinted VO_2_Nano windows, it is more acceptable than the blue one and could have further enlarged visible transmittance, i.e., to be darker brown and getting more flexibility of daylighting adjustment.

7.5 Research limitations and recommended future work

This study applied two methods to explore the performance of thermochromic windows: 1) Simulation by EnergyPlus modelling to predict energy and daylighting performance affected by different TC windows; 2) Experimental methods were used to investigate the human response and acceptance to the indoor space lit by simulated daylight through tinted TC glazing. The objective visual tests and subjective evaluation were included. When reviewing the findings, following limitations should be considered:

1) Simulation modelling is based on series of data and assumptions. Although EnergyPlus was proved to be more accurate and reliable, and showed the advantages of the TC windows when compared with the standard double glazing, the results are restricted valid for the room with specified conditions and dimensions.
2) Building standard varies according to different climatic conditions, for comparability, a common standard that would meet the requirement for most of the selected climates were used to build the simulation model.
3) For both experiments in chapter5 and chapter6, Wilcoxon signed rank paired comparison detected a difference with the practical effect but non-significance. Although the results are generally reliable and acceptable, further investigations could be carried out with increase sample size under the same hypothesis before rejecting the null hypothesis [219].
4) d2 test for sustained attention did not show any significant difference across different window conditions but obtained the significant different ratings in subjective assessment. Previous studies showed that participant with higher education performs better in d2 tests [221]. Our participants all have education levels of postgraduate, which decrease the sensitivity of detecting the effect of

various TC window conditions on sustained attention.

5) For analysis of colour discrimination test in chapter 6, it is difficult to isolate the effect of window conditions or the size of Landolt rings that cause the detected significant difference. Further investigation with a constant size of letters was necessary to provide more evidence.

Depending on the findings, some future works were recommended to make up the methodological and experimental limitations, and explore further about TC windows:

1) For future research, it is suggested that experimental measurements for building energy and daylighting should be carried out to validate the EnergyPlus model.
2) A further investigation on the performance of TC windows applied in buildings with various dimensions is suggested. Moreover, climate-dependent building standards should be considered as well.
3) The laboratory study has already detected the notable effects of tinted windows on the human response to visual performance and subjective sensations. Therefore, whether these effects exist under the practical daylighting conditions is desired to be investigated. In addition, a long-term experiment should be conducted, exploring both physical and psychological changes caused by the TC windows.
4) With regards to the statistical analysis, enlarging the sample size is necessary to get more accurate results. The effect of demographic information from the participants, such as age, gender, visual acuity levels, ethnic background, should also be analysed. In addition, the participants' temporal variables such as caffeine intake, hunger levels, fatigue levels would also be applied to support the results analysis in this study.

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Appendix A

Experimental Information

Study: Visual perception of occupants in a series of experimental conditions
Investigator: Runqi LIANG
Supervisor: Dr Yupeng Wu & Dr Robin Wilson
Advisor: Dr Sergio Altomonte & Dr Michael Kent

Explanation

This experiment aims to investigate visual perception in a small-furnished room lit by an artificial window.

Overview of experimental procedure

This experiment will consist of three sessions. Each session will follow the same experimental procedure. A 2-minute break will be taken between each session during which you will be asked to rest in a space provided outside the lab. Before you start the sessions:

1. The investigator will provide you with a detailed explanation of the experiment and you will be asked to complete a consent form.
2. You will be asked to fill in a short questionnaire to collect (anonymous) information about yourself and your perception of visual sensitivity.
3. You will be given step-by-step instructions on how to do the tests and then the investigator will give a demonstration of the full experimental procedure. During all stages of the experiment, you will have the chance to ask as many questions as needed for you to clarify the procedures of this study.

During the test sessions:

4. After the pre-test, the experimental procedure will start, and results will be collected. You will be asked to make observations and describe what you see.
5. If you cannot see parts of the test objects clearly, do not worry, make a guess or tell the investigator you cannot answer, please attempt every object and provide a response for each.

Risks

There are no significant risks or adverse effects associated with this experiment. You will be in a small experimental chamber for a short period (up to 10 mins for each session). If at any point in the experiment you feel claustrophobic (feel very uncomfortable or anxious when you are in a small enclosed space), please tell the investigator and we can halt the experiment.

Period of time required

Each experiment session will last approximately 10 minutes, and each participant will participate in three sessions in total.

Participant information questionnaire

Participant Number ______

Time_______________

Date________________

Please tick the information about yourself or fill in the blank.

1. What is your gender? ☐Male ☐Female
2. What is your age? ____
3. What is your academic background? (e.g. Engineering/Social Science, UG/PhD/research fellow, etc.) ____________________________________
4. Do you have any problems with your vision:

☐ Colour blindness ☐ Colour weakness ☐ Short sightedness ☐Far sightedness

☐ None ☐Others________________

5. If yes, do you use glasses or contact lenses to correct any eye conditions? ☐ Yes ☐ No
6. What is your eye colour?

☐Black ☐Brown ☐Blue ☐Green ☐Grey ☐Hazel ☐Red ☐Violet

☐Other_______________

7. How long have you lived in the UK? _______________________________
8. What is your ethnic background?

☐White ☐ Mixed/ Multiple ethnic groups ☐Asian

☐ Black/ African /Caribbean/Black British ☐Other ethnic group____________

9. What is current state of health? ☐ Ill ☐ Not too bad ☐Good

10. Is there any information that is not provided in the above that you feel the investigator should be aware of? If so, please state in the space provided below.____

Photosensitivity Questionnaires

Please tick the information about yourself

1. What kind of light do you consider yourself most sensitive to?
(In another word, if light level changes in a room, which light source would give rise to discomfort?)
☐Daylight ☐Electric lighting ☐Both ☐None

2. When working in a room, what kind of lighting conditions would you prefer?
☐ Bright
☐ Fairly bright
☐ Fairly dim
☐ Dark

3. What kind of light source do you prefer when working in a room?
☐ Daylight
☐ Combination of daylight and electric light
☐ Electric lighting

4. What kind of electric lighting do you prefer in the working environment?
☐ Cool (bluish) white
☐ Warm (reddish) white

5. When working at your desk how often you do use window blinds?
☐ Never (always up)
☐ Sometimes
☐ Quite often (half time down, but adjusted)
☐ Often
☐ Always (always down)
☐ Have no window blinds

Temporal Subjective Fatigue Scales

1. Please select the word most describes your state of fatigue at this moment

☐ Fully alert, wide awake
☐ Very lively, responsive, but not at peak
☐ OK, somewhat fresh
☐ A little tired, less than fresh
☐ Moderately tired, let down
☐ Extremely tired, very difficult to concentrate
☐ Completely exhausted, unable to function effectively

2. Are you hungry now?

☐ Too hungry, starving , and need something to eat
☐ Hungry, cannot ignore
☐ Slightly hungry, would like to have a snack
☐ Neutral, satisfied, but feel you are getting hungry
☐ Slightly full, will not be hungry for some time
☐ Full, do not want anything to eat
☐ Too full, almost uncomfortable

3. Did you have anything containing caffeine today? (e.g. drinks such as tea, coffee and cola or pills, bars and gum containing caffeine)

☐Yes ☐No

4. If you answered 'Yes' to question 3, how many servings have you had today? (e.g. one medium latte with an extra shot, three pieces of caffeine gum, etc.)

____

And when did you have it today? (e.g. a latte 30 mins before the test)

____

5. Do you normally have caffeine during a working day? ☐Yes ☐No

6. If the space you usually work at is indoors, is it predominantly lit by

☐Daylight ☐ Electrical lighting ☐ I don't work indoors

7. If you answered 'Daylight' to question 6, does your work area have good access to daylight? ☐Yes ☐No

8. Please select the word most describes your state of sleepiness at this moment.

- ☐ Very alert
- ☐ Between very alert and alert
- ☐ Alert – normal level
- ☐ Just below alert – not quite at optimum level
- ☐ Neither alert nor sleepy
- ☐ Slightly drowsy
- ☐ Sleepy, but no effort required to stay awake
- ☐ Between sleepy and very sleepy
- ☐ Very sleepy, great effort required to stay awake

PARTICIPANT CONSENT FORM

Project title: Visual perception of occupants in a series of experimental conditions
Researcher's name ……Runqi LIANG…………………………………………
Supervisor's name ……Yupeng WU, Robin Wilson……………………………

- I have read the Participant Information Sheet and the nature and purpose of the research project has been explained to me. I understand and agree to take part.

- I understand the purpose of the research project and my involvement in it.

- I understand that I may withdraw from the research project at any stage and that this will not affect my status now or in the future.

- I understand that while information gained during the study may be published, I will not be identified and my personal results will remain confidential.

- I understand that the anonymised data are approved for use in secondary studies.

- I understand that data will be stored in a locked filing cabinet, digital data will be stored only on a password-protected computer and on a secure server. Only researchers and supervisors can get access to the data. At the end of the researcher student's project, all data from the study will be passed on to academic supervisors and the supervisors will then have responsibility for the storage of the data. In accordance with the Data Protection Act, the data will be kept securely for seven years following the publication of results. After this time, electronic files will be deleted and any hard copies will be destroyed.

- I understand that I may contact the researcher or supervisor if I require further information about the research.

Signed ……………………………………………………… (Research participant)

Print name…………………………………Participant No. …………………

Signed………………………………………………………… (Investigator)

Print name ………………………………… (Investigator) **Date** ………………

Contact details

Researcher: Runqi.Liang@nottingham.ac.uk
Supervisors: Yupeng.Wu@nottingham.ac.uk, Robin.Wilson@nottingham.ac.uk

Appendix B

Experimental Information

Study: Visual attention effected by different experimental conditions
Investigator: Runqi LIANG
Supervisor: Dr Yupeng Wu & Dr Robin Wilson
Advisor: Dr Sergio Altomonte & Dr Michael Kent

Explanation

This experiment aims to investigate visual attention of people working in a small-furnished room lit by an artificial window.

Overview of experimental procedure

This experiment will consist of five sessions. Each session will follow the same experimental procedure. A 2-minute break will be taken between each session during which you will be asked to rest in a space provided outside the lab. Before you start the sessions:

1. The investigator will provide you with a detailed explanation of the experiment and you will be asked to complete a consent form.
2. You will be asked to fill in a short questionnaire to collect (anonymous) information about yourself and your perception of visual sensitivity, including age, ethnics, etc.
3. You will be given step-by-step instructions on how to do the tests and then the investigator will give a demonstration of the full experimental procedure. During all stages of the experiment, you will have the chance to ask as many questions as needed for you to clarify the procedures of this study.

During the test sessions:

4. After the pre-test, the experimental procedure will start, and results will be collected. You will be asked to do the observations and finish the tasks.
5. There is time limit for each observation, please finish them as fast and accurate as possible.

Risks

There are no significant risks or adverse effects associated with this experiment. You will be in a small experimental chamber for a short period (up to 10 mins for each session). If at any point in the experiment you feel claustrophobic (feel very uncomfortable or anxious when you are in a small enclosed space), please tell the investigator and we can halt the experiment.

Period of time required

Each experiment session will last approximately 10 minutes, and each participant will participate in five sessions in total.

Participant information questionnaire

Participant Number ______ Time_______________ Date________________

Please tick the information about yourself or fill in the blank.

1. What is your gender? ☐Male ☐Female
2. What is your age? ____
3. What is your academic background? (e.g. Engineering/Social Science, UG/PhD/research fellow, etc.) ____________________________________
4. Do you have any problems with your colour vision:
   ☐ Yes ☐ No
5. Do you wear glasses or contact lenses to correct any eye conditions?
   ☐ Yes ☐ No
6. What is your eye colour? ____
7. What is your ethnic background?
   ☐White ☐ Mixed/ Multiple ethnic groups ☐Asian
   ☐ Black/ African /Caribbean/Black British ☐Other ethnic group____________
8. What is current state of health? ☐ Ill ☐ Not too bad ☐Good
9. What kind of light do you consider yourself most sensitive to?
   (In another word, if light level changes in a room, which light source would give rise to discomfort?)
   ☐Daylight ☐Electric lighting
10. When working in a room, what kind of lighting conditions would you prefer?
    ☐Bright ☐Fairly bright ☐Fairly dim ☐Dark
11. What kind of light source do you prefer when working in a room?
    ☐Daylight ☐Electric lighting
12. What kind of electric lighting do you prefer in the working environment?
    ☐ Cool (bluish) white
    ☐ Warm (reddish/yellowish) white
13. Is there any information that is not provided in the above that you feel the investigator should be aware of? If so, please state in the space provided below.

    ____

Temporal Subjective Fatigue Scales

1. Please select the word most describes your state of fatigue at this moment

☐ Fully alert, wide awake

☐ Very lively, responsive, but not at peak

☐ OK, somewhat fresh

☐ A little tired, less than fresh

☐ Moderately tired, let down

☐ Extremely tired, very difficult to concentrate

☐ Completely exhausted, unable to function effectively

2. Are you hungry now?

☐ Too hungry, starving, and need something to eat

☐ Hungry, cannot ignore

☐ Slightly hungry, would like to have a snack

☐ Neutral, satisfied, but feel you are getting hungry

☐ Slightly full, will not be hungry for some time

☐ Full, do not want anything to eat

☐ Too full, almost uncomfortable

3. Did you have anything containing caffeine today? (e.g. drinks such as tea, coffee and cola or pills, bars and gum containing caffeine)

   ☐Yes ☐No

4. If you answered 'Yes' to question 3, how many servings have you had today? (e.g. one medium latte with an extra shot, three pieces of caffeine gum, etc.) ____________________________

And when did you have it today? (e.g. a latte 30 mins before the test)

____

5. Do you normally have caffeine during a working day? ☐Yes ☐No

PARTICIPANT CONSENT FORM

Project title …… Visual attention effected by different experimental conditions ……

Researcher's name ……Runqi LIANG…………………………………………

Supervisor's name ……Yupeng WU, Robin Wilson……………………………………

I, the undersigned as a research participant, confirmed that (please tick as appropriate):

1	I have read the Participant Information Sheet and the nature and purpose of the research project has been explained to me. I understand and agree to take part.	☐
2	I understand the purpose of the research project and my involvement in it.	☐
3	I understand that I may withdraw from the research project at any stage and that this will not affect my status now or in the future.	☐
4	I understand that while information gained during the study may be published, I will not be identified and my personal results will remain confidential.	☐
5	I understand that the anonymised data are approved for use in secondary studies.	☐
6	I understand that data will be stored in a locked filing cabinet, digital data will be stored only on a password-protected computer and on a secure server. Only researchers and supervisors can get access to the data. At the end of the researcher student's project, all data from the study will be passed on to academic supervisors and the supervisors will then have responsibility for the storage of the data. In accordance with the Data Protection Act, the data will be kept securely for seven years following the publication of results. After this time, electronic files will be deleted and any hard copies will be destroyed.	☐
7	I understand that I may contact the researcher or supervisor if I require further information about the research.	☐

Signed ……………………………………………………………… (Research participant)

Print name ………………………………………………Participant No. …………………

Signed ……………………………………………………… (Investigator)

Print name ………………………… (Investigator) **Date** ……………………………

Contact details

Researcher: Runqi.Liang@nottingham.ac.uk

Supervisors: Yupeng.Wu@nottingham.ac.uk, Robin.Wilson@nottingham.ac.uk