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Development of a View Perception Quantifying Method for a Holistic Window Performance Assessment Using a Virtual Environment

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Abstract

Working Environments designs shape occupants' health and well-being. One of these design parameters is window design and its impact on view perception. The view is the transmitting visual information carried by daylight into the buildings providing a connection to the outdoor environment. There are significant gaps in our understanding of the window-occupant relationship that characterises the view quality perception, partially due to the difficulties combined with methodologies used in daylight studies and the absence of studies with a holistic approach to understand such relationship. In response, this thesis developed an inclusive methodology that could be used to evaluate view perception in three stages. The first stage incorporated the development and validation of an alternative visual representing environment that reflects the luminous characteristics of a real one using physically-based virtual reality technique. The collection of photometric properties and visual responses in real and virtual settings and the analysis of the collected data established the validity of the proposed methodology as an alternative representation method to study visual perceptions. The second stage included the development of a comprehensive assessment method to quantify view perception based on two case studies. The first study investigated variations in view perception resulted from different observing locations using subjective and objective (physiological) evaluations. The same assessment method was applied to the second study to assess the variation in view perception from different window sizes. The results of the second study were assessed in the third stage against optimised window sizes for energy and daylighting performance to provide a holistic window performance; as view perception, energy, and daylighting window performance are usually studied separately in the literature. Further reliability and

correlation analyses were conducted on the data collected from the two studies on view perception to provide a refined methodology for future evaluations of view perception.

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List of Publications

Abd-Alhamid, F., Kent, M., Calautit, J., Wu, Y., *Developing an Innovative Method for Visual Perception Evaluation in a Physical-Based Virtual Environment. Building and Environment*, 2019. **162**: p. 106278.

Abd-Alhamid, F., Kent, M., Calautit, J., Wu, Y., *Evaluating the impact of viewing location on view perception using a virtual environment.* Building and Environment, 2020: p. 106932.

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List of Abbreviations

WWR	Window to Wall Ratio
HDR	High Dynamic Range
PANAS	Positive and Negative Affect Schedule
ANS	Autonomic Nervous System
SNS	Sympathetic Nervous System
PNS	Parasympathetic Nervous System
SC	Skin Conductance
SCR	Phasic Skin Conductance
SCL	Skin Conductance Level
HR	Heart Rate
HRV	Heart Rate Variability
HF-HRV	High Frequency Heart Rate Variability
LF-HRV	Low Frequency Heart Rate Variability
LF/HF	Low Frequency Heart Rate Variability To High Frequency Heart Rate Variability Ratio
VLF	Very Low Frequency
ULF	Ultra-low frequency
HRV_a	Heart Rate Variability Aplmplitude
BVA	Blood Volum Puls Aplmplitude
VR	Virtual Reality
CCT	Correlated Colour Temperature
ρ	Reflectance
HDRI	High Dynamic Range Image

LDRI	Low Dynamic Range Images
EV	Exposure Values
f	Aperture size
v	Shutter speed
RMSE	Root-Mean-Square-Error
MAD	Mean Absolute Deviation
C	Contrast
L_b	Background luminance
L_t	Target luminance
VAS	Visual Analogue Scale
SSQ	Simulator Sickness Questionnaire
SD	Standard deviation
CC	Characters contrast
CN	Colour naming
r	Effect size
p	Significance value
M_{dn}	Median
C	Close
M	Middle
F	Far
SPS	Samples Per Second
μS	Micro Siemens
η_p^2	Partial eta squared
DF	Daylight Factor
df	Degree of freedom

DA	Daylight Anatomy
UDI	Useful Daylight Illuminance
IWEC	International Weather For Energy Calculation
U-value	Thermal transmittance
N	Number of participants
F	Test statistic
IQR	Interquartile Range
χ^2	Test statistic
t	Test statistic
z	Z-score
POMP	Percent of Maximum Possible
r_s	Spearman's correlation coefficient

Chapter 1

Introduction

1.1 Introduction

Indoor environmental quality has a major impact on how occupants perceive the different physical aspects of their immediate environment which may affect their comfort, productivity, health, and well-being. Views provided by windows are key factors that affect the indoor environmental quality perception [1] and has an impact on occupants overall psychological and physiological comfort; as high-quality views have led to higher satisfaction with the working environment and fewer self-reported discomfort [2].

Views could be considered as the perceived visual messages by the human perceptual system that are transmitted into the building using daylight [3, 4] (Figure 1-1). I.e., daylight reflected from outside surfaces carries visual information and enters into the building through windows, which is perceived by building occupants as the view. Accordingly, daylight could be referred to as a carrier of outdoor view.

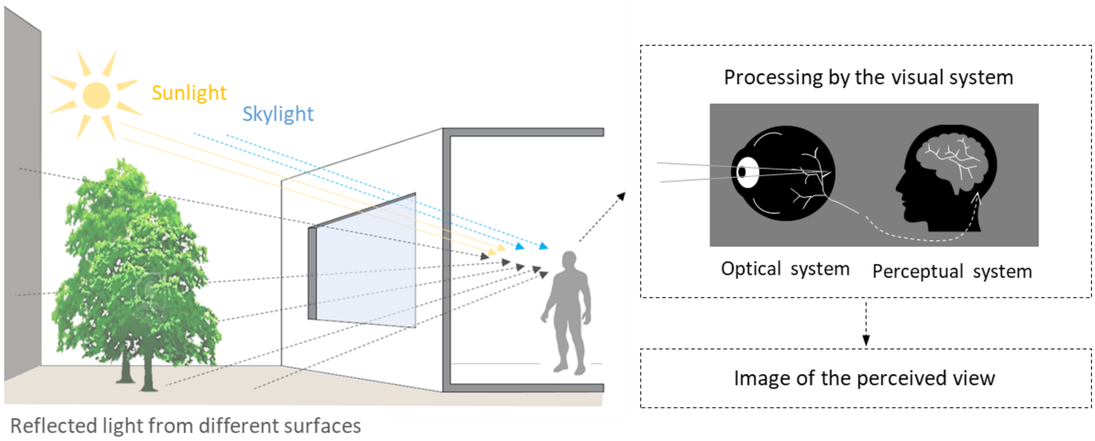


Figure 1-1. Schematic of the view perception process based on Tregenza & Wilson [3, 4] definition of view

In previous studies, views and daylight are usually investigated independently considering the view as what is seen outside the window while the daylight is the illuminance transmitted through the window. Only few studies have considered both factors to assess visual comfort inside buildings by investigating the impact of perceived interest of the view on glare acceptance [5-7] which showed higher accepted thresholds of discomfort glare with increasing interest in the corresponding view. However, the factors affecting how interesting the view is (i.e., high quality view) have not been completely characterized yet and insufficient information is known about the view preference.

One reason behind this might be the need to quantify view quality to build reference data on view preference. Studies on view preference usually highlight the preference of natural views over the built urban views [2, 5, 6, 8-11]. However, it is still not clear what makes a view preferred apart from its naturalness, and a comprehensive method to characterize view perception is required as natural views are not equally attractive, nor all urban views are the same. For urban views in high-density urban areas, in which the natural components are minimal, the factors that contribute to view preference are not fully understood yet.

View quality perception can also be affected by the window size. Several studies have been conducted to assess window size preference and reported window sizes were considered concerning the wall area (i.e., window to wall ratio WWR); however, results indicated inconsistent conclusions and people were satisfied with different window sizes (e.g., 35 % [12], 25 to 30 % [13], 50 and 80 % [14], 40 % [15], 100 % [16]). Experiments would often use different methods of collecting subjective ratings of views from windows and this may be one reason why studies found inconsistent results. Another might be the fact that these studies are relying on subjective ratings only, which are often subjected to methodological biases [17]. Furthermore, the experimental settings in different window view studies have varied as some studies used 2-dimensional representation methods [6, 7, 11, 18] whereas, in other experiments, reduced-scale models using fixed viewing position were used [12-14, 19]. Such experimental settings were often utilized to control the continuous changes in the daylit environments [20-22]. Another reason might be the relative difficulty in setting up and manipulating the investigated variables when real windows are used [5]. Nevertheless, the relation between the observer location and view perception is not encountered in such experimental sittings as they often use a fixed observer location; hence, the perceived view across different locations in the same room and the size of the view in the observer field of view are not considered.

Other factors that might affect view perception are the different window design optimizing methods (e.g., WWR, glazing, shading, etc.). The focus of such studies has been limited to lighting and energy performance optimization [22-25] without considering the corresponding view quality perceived through these window systems, and their impact on connection to outdoors has not been identified yet.

In order to quantify view perception more accurately, there is a need to develop an inclusive multi-criteria approach that can be utilized to evaluate view perception. This is important for future studies on window design and a comprehensive understanding of view perception.

1.2 Aim and Objectives

This study was designed with the aim to develop a refined comprehensive method to evaluate view perception in the office environment. A Systematic experimental approach was established to address the above-discussed gaps through developing an alternative visual representation method that can reflect the luminous characteristics of a real environment and by developing a comprehensive subjective and objective evaluation method to quantify view perception. This aim was accomplished by four detailed objectives:

(1) develop and validate a virtual reality environment to be used as a representation of a real luminous environment to control the outdoor dynamic changes in photometric parameters and view content, to provide a consistent testing environment for all the participants;

(2) develop a comprehensive method to quantify view perception by collecting subjective and objective responses to view perception at different observing locations in a typical cellular office as a case study;

(3) conduct a threefold multi-criteria analysis to optimize window design based on lighting and energy simulation and view perception using different window sizes for the same office in the second objective as another case study;

(4) provide a refined methodology on view perception using in-depth statistical analysis on the data obtained in the two case studies to provide guidance for future studies on view perception.

1.3 Thesis Outline

The outline below demonstrates the different steps that have been performed to design and conduct the experiments, analyse the collected data, infer the results, and draw conclusions of this course of work. This thesis follows the structure of a PhD by publication incorporating four journal publications presented in the appendices. Following the introduction and literature review chapters, the methodology used to conduct several experiments, from which the publications have emerged is explained. Afterwards, a chapter that provides an overview of the four papers and links them together is presented and the thesis concluded with conclusions and future research. The thesis structure is outlined hereunder.

Chapter 1. Introduction: This chapter introduces a brief overview of issues in view perception, demonstrates an outline of the thesis contents, and illustrates the aim and objectives of this thesis.

Chapter 2. Literature Review: Views through windows and the existing view representation and assessment methods are reviewed in this chapter. A comprehensive review of studies on parameters that affect view perception quality is presented documenting the studies that were used to establish this course of work.

Chapter 3. Methodology and Experiments Overview: The research methodology followed in this research is presented in this chapter. The development of the methods used to elicit participants subjective and objective responses in different stages of the research are described. A chronological overview of the experiments conducted at different stages of the research is presented in this chapter with reference to the corresponding papers, indicating the relationship between the different experiments conducted in this work.

Chapter 4. Conclusions: The results from the papers are discussed in this chapter and conclusions are drawn. The limitations of this study are illustrated, and future studies based on this work are proposed.

Chapter 2

Literature Review

2.1 Introduction

Several studies have been conducted to highlight the importance of providing access to view or daylight for buildings occupants' health and well-being [11, 26-29]. Views are one of the indoor environmental quality factors which affect occupants' perception of the environment [1]. Those views are transmitted into the building via daylighting which is highly desired by building occupants [30] and preferred over artificial lighting as the main source of illumination [31].

Views are preferred for providing different visual content to what is seen within the interior space. They are continuously dynamic, unlike the monotonous indoor environments. The daylight transmitting the view changes continuously in intensity, colour, diffuseness, and direction [32]. In addition, outside elements constructing the views also change (e.g., clouds movement, objects shadows, trees changing colours or losing leaves, flowers appearing in certain seasons, pedestrian walking, vehicles movement, etc.) as indicated in Figure 2-1.

Figure 2-1. Change in view provided as trees completely shed their leaves in winter (left) compared to summer (right)

A view with high information content is more desirable [8] for providing access to environmental information, sensory change, connection to the world outside, and restoration and recovery as explained by the psychological benefits of view [33].

The access to environmental information comprises the ability to access information about weather and time of the day, which is an important factor in window preference [34]. Visual information from views also offers connection to the outside world (i.e., events occurring outside), which also influences people preference of daylight over interior artificial lighting even though sufficient illuminance is provided [12].

The access to sensory change represents how humans perceive the environment via sensory perception interaction, which is promoted by the dynamic feature of outdoor visual and acoustic environment compared to the unchanging conditions in the indoor environment. The importance of the sensory change can be inferred by the negative perceptions of monotonous environments (i.e., boredom, restlessness, lack of concentration, and hallucinations) reported by occupants of unvarying interior environments (e.g., ventilation rate, temperature, artificial lighting, colours, and furnishings) [33]. Consequently, views through windows could be the only factor providing variable environmental stimulation for sensory change.

Restoration and recovery provided by views have a positive impact on people’s health and well-being by providing relief from pain [27] and stress [31] via offering a pleasing change to the eye and mind [33]. The impact of views on eyes’ health was established in ophthalmological studies on eye strain usually reported in computer-based working environments; highlighting the necessity of frequent changes in eye focus distance to provide brief periods of relaxation for the eye muscles [35]. This could be provided by distant elements seen from windows which can minimise the eye strain by providing an alternative focus point at which to gaze [2]. Another way by which views can enhance people’s health and well-being is by reducing stress. Views with nature content found to be more restorative than man-made built views [26, 28, 29]. This was found in a study in a healthcare environment where patients assigned with views of a natural scene recovered faster than those recovering in rooms with views of a brick building wall [27]. Similar findings were obtained in a prison environment as less stress-related symptoms were reported by residents in rooms with a view of a surrounding hill compared to those with views of an interior courtyard [28]. In office environments, views with natural elements were found to alleviate the negative impact of workers' reported job stress; hence, improve their well-being [26].

These findings were confirmed with studies that utilised physiological measurements. In one study, after being subjected to a stressful movie, subjects were asked to observe one of six different natural and urban settings using sound/coloured videotapes [29]. Stress was measured using subjective self-ratings and physiological measurements of heart rate, muscle tension, and skin conductance. The results indicated enhanced recovery rates when observers were exposed to natural scenes compared to scenes with urban content.

Similar findings were reported by a psychophysiological study on the impact of natural views and indoor plant on the human response in workplace environments [11]. In this study, subjects' psychophysiological response was assessed while viewing six images displayed on a screen including a view of a city, a view of a city and indoor plants, a view of nature, a view of nature and indoor plants, a windowless environment, and a windowless environment with indoor plants. The results of the psychophysiological measures indicated that participants were less anxious when watching a view of nature and/or when indoor plants were presented, whereas a higher degree of tension and anxiety was experienced when neither the window view nor the indoor plants were shown.

Despite daylight and view preference, daylight might negatively affect visual comfort when glare perception is presented. Yet, when an interesting view is transmitted by the daylight, glare tolerance found to increase as the view from windows plays a psychological role in lessening the glare sensation [6].

The view impact on glare perception was introduced early by Hopkinson [36] who suggested that glare sensation from a daylight source is tolerated more than the glare from artificial lighting of the same size and brightness. Accordingly, it was hypothesised that the associated view contributes to this tolerance [37]. Another study suggested that the glare issue could be ignored when the office rooms are provided with a pleasant window view due to users' acceptance of higher levels of glare resulted by daylight [38]. This led to a few studies to investigate some of window view characteristics and their influence on discomfort glare ratings.

Using projected screen images from small glare source, the interest in view for its naturalness, and horizontal stratification (i.e., a number of horizontal layers seen within the image including a layer of ground, a layer of city or landscape, and a layer of the sky [8]) was investigated and the study concluded that the view naturalness, presence of water, and presence of the ground produced less glare discomfort ratings. This was further confirmed in another study on daylight glare assessment [6]. Other view features including complexity, coherence, legibility, and mystery were investigated to assess their impact on glare perception [39]. Views with high levels of such features found to be less glaring in a small projected screen images study, while under daylight conditions, the results were only verified for complexity and mystery. Near and distant natural and man-made views were investigated in another study on the glare-view relationship using an artificial window [7]. The study found that distant urban views are the least glaring, which contrasts with previous studies which indicated that the natural scenes were found to be less glaring [5, 6].

Window views can enhance building occupant’s performance. When occupants are exhausted, their performance will be negatively affected, especially in high concentration tasks which affect their emotion; contributing to irritability behaviour [40]. Natural views from windows showed the ability to maintain people’s ability to concentrate over long periods by mitigating stress via helping in its recovery [41]. Performance in tasks requiring concentration, such as digit span forward and backward tests, was found to be enhanced for residents of rooms with natural views compared to those living in rooms with man-made views [42]. Similarly, in a school environment study [43], results indicated that pleasant window views that contain vegetation or human activity and distant objects have improved outcomes of student learning.

In a study conducted in an office environment [40], improved worker performance was associated with pleasant and sufficient views from windows, which also was found to be the most significant variable related to enhanced working performance. Workers’ performance was found to be up to 12% faster when they had a larger view angular size with more vegetation compared to those with no views. The window view importance was inferred by a high level of reported fatigue associated with lack of window view. However, the view was found to improve performance only if no glare was perceived from the window; thus, a good balance should be provided when windows and shading devices are designed so that views can be seen without the risk of glare.

The introductory literature review clearly demonstrates the importance of view in psychological and physiological well-being of occupants of indoor environments and highlights the need to quantify ‘high-quality views’ that can attain the psychological and physiological benefits of view.

The attractiveness of the view was subjectively assessed in glare studies based on its nature content. It is still unclear what makes a view attractive (i.e., a high-quality view) as the reviewed studies above focused on naturalness and horizontal stratification; i.e., another way to characterise view preference or attractiveness is needed as natural views are not equally attractive, nor all urban views are the same. For the urban views in high-density urban areas in which natural elements are minimal, other factors contribute to view preference and would be interesting to investigate. View content elements (e.g., water, trees, and people, etc.,) and other characteristics, such as movement, colours, and climatic conditions, which can affect view preference, also need to be investigated. In addition, the same view can appear differently in different times of the day and in different seasons; for instance, deciduous trees will lose all their leaves in winter, and colours of both nature and urban views will appear different based on different sun positions and sky conditions (e.g., clear, cloudy, and correlated colour temperature, etc.); affecting perceived view preference. In addition, glare resulting from daylight can affect occupants’ performance; raising the issue of what constitutes a sufficient amount of view needed to sustain connection with the outdoor environment when shading devices are introduced.

In the following sections, factors affecting view quality including content related factors, horizontal stratification, design-related factors such as window’s shape and size, dynamic changes in views, and view quantity, besides view representation and assessment methods are reviewed.

2.2 View Quality Assessment

View quality can be achieved via the interaction of several factors which produces a high-quality view. View quality within the built environment has been mainly discussed in literature based on the discrete attributes of quality instead of the interaction between them. These attributes comprise content-related factors including naturalness (nature scenes vs man-made scenes), movement elements (people, street, cars, clouds), horizontal stratification (sky, middle layer, ground), design-related factors (window's shape and size, shading devices, mullions, and partitions), dynamic changes in views based on observer-related factors (eye level and proximity to the window), and view quantity.

The view quantity is not limited to the window to wall ratio, as the interaction of observer position (proximity to view and amount of view within the visual field) and fractured views by shading devices affect the quantity of views provided. Thus, view quality and quantity are interrelated terms as insufficient quantity of view will result in low-quality views which can depend on window or observer related factors.

View quality and quantity interactions can eventually affect the basic psychological benefits of the window proposed in the literature [33]. Based on the reviewed studies on view perception, a model of interaction between quality attributes and psychological benefits is proposed in Figure 2-2.

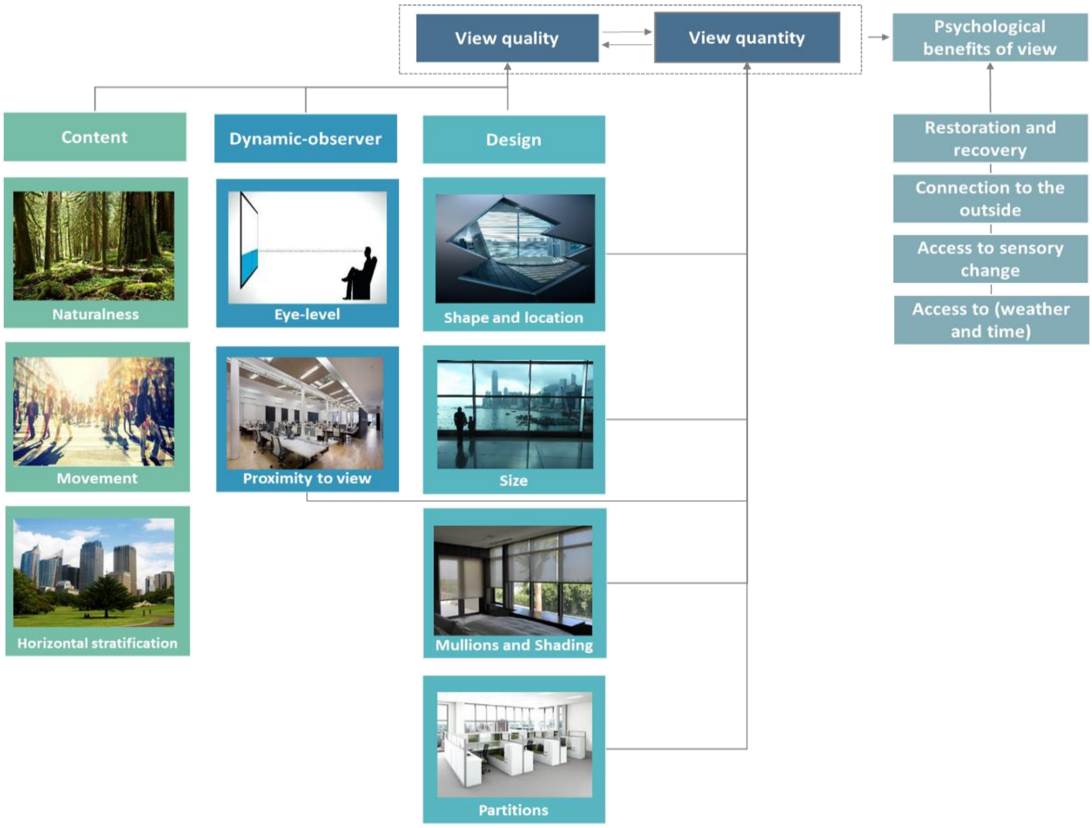


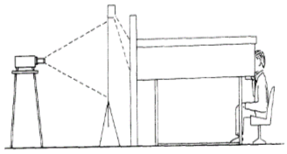
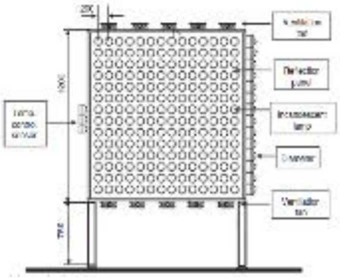
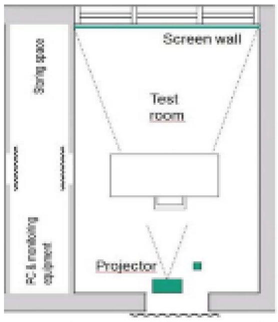
Figure 2-2. Graphical abstract for view perception influencing factors of quality and quantity attributes and their interaction with psychological benefits of view based on reviewed studies [8, 12-14, 18, 19, 33, 44, 45]

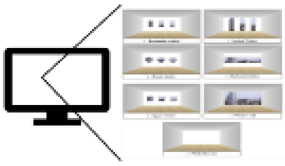
The model suggests that high-quality views from windows can be achieved via the interaction of several factors; for example, the size of the window can affect the view provided within the room, and the window position on the wall will affect the layers of view seen through the window as a result of the relation between the window and the observer location within the room or their eye level (Figure 2-3). The studies reviewed in this regard, besides the view perception in sustainable building standards, are discussed in the following sections.

Figure 2-3. The interaction between different view quality factors: (a) the change in the layer of view seen due to the window position; (b) the change in view content due to the window layout and size; (c) the change in content seen due to change in observer location when moving left and right.

The reviewed studies have utilised various experimental setups (i.e., view representation methodologies) which can be divided into two categories: those using daylight from real windows, and those using artificial lighting and images that are projected or displayed on screens to simulate the real environment as illustrated in Table 2-1.

Table 2-1. Illustration of view representation methods usually used in view studies

Study Purpose	Method	Illustration	Ref.
View size and position preference	Projected images through aperture in reduced-scale model		[13, 14, 19]
View size preference	Reduced-scale model and real view		[12]
View and glare	Printed Images placed on simulated artificial window		[7]
View interest and glare	Pictures projected from wall aperture on a tracing paper screen		[6, 39]
View size preference and light distribution	Projected views on screen wall		[15]
View content preference	Images displayed on monitor screen		[11]
View size	Images displayed on high dynamic rang (HDR) screen		[18]

Window size and shape	3D simulation displayed on screen		[16]
View clarity through fabric shading	Real window views		[45]

The methodologies' advantages and disadvantages are discussed in section 2.4 and a new methodology to represent views is proposed.

2.2.1 View Content

One factor that affects the satisfaction with the provided view is view content [8], which might be assessed by its naturalness, movement, and horizontal stratification of three layers of the sky, the middle layer of cityscape or natural elements, and the ground. The sky provides information about weather, time of the day, and seasonal change, while the middle layer provides information about the inanimate environment, and the ground layer is where social activities take place and it includes the movement of pedestrians, rivers, etc.

Naturalness preference over man-made built views is well established in the literature and found to affect individuals' health and well-being [11, 26, 29]. This was explained by Biophilia theory which states that humans have an inherent tendency to connect with nature [46] which is depleted in cities and indoor environments where man-made objects are dominant.

However, the amount of naturalness needed in order to feel this connection is not well understood nor what makes a city-view more acceptable. In a large-scale study on view content preference in a healthcare setting, patients were asked to rate their preferences for photos of different views [47]. The study indicated that nature-dominant and distant views were the most favoured while views of industrial settings and vehicles were rated most negatively. However, the natural views were not constantly more desirable than urban views and the study suggested that the view preference is mainly due to the aesthetic feature of the view content.

One attempt to assess view content quality from windows was found based on a point system for a series of questions as shown in Figure 2-4 [9]. Accordingly, the view was considered as low quality (<4 points), medium quality (5-7 points), or high-quality view (>8 points). This method was established based on the findings of existing studies on view content and subjective preference. The points are given based on the naturalness of view, the number of layers seen within the view, natural water and presence of traffic, diversity, and building features - whether old, modern, simple, or complex.

In the rating system, the most weight was given to naturalness of the view; however, this assumes that all nature scenes are similar which is not the case in different climatic regions and different seasons of the year. This method was verified only by subjective assessment in the Netherlands; however, it needs verification with different populations and with objective measures. Other view impacting factors including shading devices and glazing types, and other view contents like colour, climate, movement, and presence of people and living organisms need to be considered.

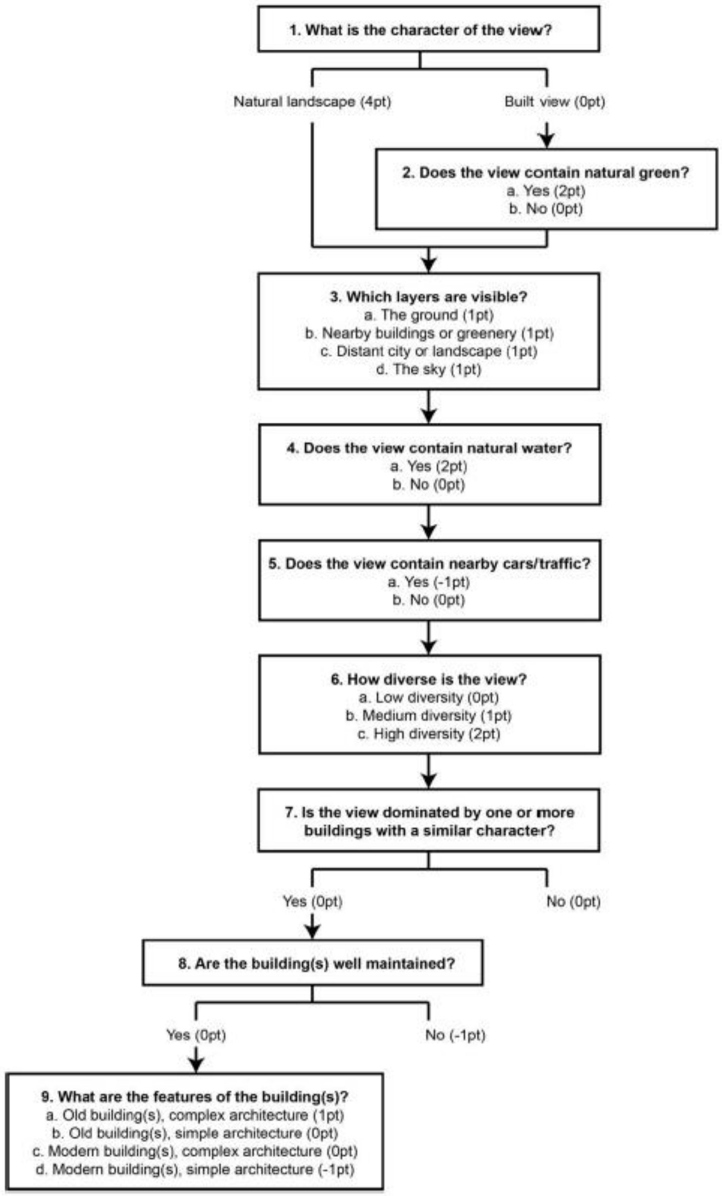


Figure 2-4. View quality assessment method proposed in [9]

2.2.2 Design-Related Factors

Other factors contributing to view quality are view size and view fracturing by shading devices, mullions, and partitions, all affecting the quantity of view provided. View size and view fracturing were first discussed in Markus' work [8], which proposed that window size should be based on communication factors through the aperture to provide pleasure from perceived sunlight and information content acquired by the view. Nevertheless, this should be considered along with providing privacy to avoid the negative visual communication of being overseen or being seen and avoiding fracturing to reduce the interruption of view when shading devices are used. Thus, it was suggested that view satisfaction with a given window is a function of size, room size and proportion, distance of exterior elements seen through windows, and information content. In literature, studies determined the quantity of view based on geometric calculations of view seen through shading systems; while other studies attempted to find the accepted window size based on subjective assessment (i.e., via asking subjects to report their preferred window size or their satisfaction with the window size provided) [12, 13, 48]. Design factors including view size and shape and view fracturing by shading devices are presented in the following sections.

2.2.2.1 View Size and Shape

In a study on view size, the critical minimum acceptable window size using subjective evaluation was investigated using a reduced scale model with one aperture representing the window with adjustable width, and rear and side apertures through which the observer can look to a real urban view [12]. The acceptable minimum window width was assessed under different conditions including outside view distance, different times of the day, daylight illumination levels, viewing aperture (rear and side), and two heights of window (7 ft (2.10 m) and 5 ft (1.50 m)). In addition, the reduced scale room area was manipulated using mirrors and movable walls. The results of this study indicated that the accepted minimum window is 35% WWR with a minimum width of 7 ft (2.10 m). Wider windows were preferred for views with near objects, which was explained by the need for intelligible information about the outside world as views with distant objects are more comprehended. It was concluded that the critical minimum size was mainly controlled by the visual information provided by the view than the amount of daylight reaching the room, the level of interior artificial lighting, the viewing aperture, or by the time of the day. The study clearly established subjective preferences of window size in relation to view content; however, in more realistic scale studies, view impact and preference might be different. Also, the impact of different positions within the room could not be investigated due to the limitation of the reduced scale model.

Another study was conducted to assess the subjective preferred layout and location of a 20% window to wall ratio (WWR), using reduced scale model and eight different views projected on a screen [13]. The preferred window layout was a horizontal aperture, 1.30 m high and 2.90 m wide (giving a 0.45 height to width ratio (i.e., aspect ratio)), while the window location preference was changed to include the skyline for distant views. For fully obstructed views, results were not consistent because of the loss of important visual cues; nevertheless, a horizontal shape was preferred similar to the previous study [12]. The study was expanded to further investigate the preference of window location which was found to be related to some features of the view (i.e., it is lowest for the distant view, highest for the scene having an elevated skyline, and falls to an intermediate value for the built view) [19]. In both studies, the degree of acceptability of these dimensions and position was not considered in comparison to smaller or larger windows (i.e., only 20% WWR was investigated). Furthermore, only cityscape views were considered, and other factors related to the room such as dimensions, layout, lighting, and those related to the observer location within the room were not considered. The views were observed through a window in a reduced scale model; thus, real scale windows might reveal different findings.

Another study that assesses the subjective preference of window size was conducted using a reduced scale model [14]. It showed that a window of size between 50% and 80% WWR was preferred. The study indicated that distant panoramic views require wider aperture while narrower apertures should be used for near views with a higher skyline; contradicting previous findings [12, 13]. The study suggested that neither exclusively man-made views nor natural views are preferred, and the position and dimensions of the window might be affected by the need to contain natural elements within the view.

The previous findings were questioned by a survey study [44], in which window preference in terms of number (one or two), size (small, medium, large), and degree of transparency (clear or translucent) in variety of spaces was investigated. The underlying factors for these preferences were examined by means of subjective rating for window preference in different types of settings (i.e., room function). Results indicated that people's preferences depend on setting type and the need for a window in that setting (i.e., larger windows are preferred for weather and temporal information while smaller windows are preferred when only ventilation or privacy are needed). The study indicated that no absolute preferred size can be determined in isolation of both setting type and task performed within the setting and view content; yet, the study was conducted using questionnaires and the actual size of windows was not given or assessed in systematic experimental means, which is needed in order to confirm the results.

The reviewed studies above provided insight into window design preference in relation to views. However, view preference was only assessed using reduced scale models without validation of the results against real settings, which limits the ability to assess view preference as the impact of real window scale in real rooms, with different sizes and proportion, was not considered but could affect window-view size preference [8]. The dynamic aspects of the view-window relationship and the depth factors could not be assessed when reduced scale models are used (i.e., by moving the observer around the room) presenting another limitation of the view representation method. Furthermore, the studies were limited to window preference in office environments in which occupants do not usually look at the window to enjoy the view as much as to feel connected to the outdoor and to receive a sense of relief; thus, the view existence (partially or completely) in occupants' field of view effect on their performance and well-being might be more suitable qualities to investigate.

In a recent study [15], employees' satisfaction with window size (i.e., to what extent the subjects are satisfied with window size, number of windows, and the width and the height of the windows) was assessed in a true scale room with projected views with three window sizes including 10%, 25%, and 40% WWR, each with three configurations as indicated in Figure 2-5. The results showed that a 10% WWR was found to be extremely unsatisfactory, while a 40% WWR with three apertures was preferred, which is consistent with previous studies that indicated a horizontal alignment preference [12, 13]; however, with a smaller aspect ratio (0.30).

Figure 2-5. The nine window conditions investigated [15]

Although the scale limitation of previous studies was addressed, neither different positions of the observer nor objective measures to quantify view were considered and only one view content was investigated.

Another study assessed subjective preference for different window shapes and sizes using 3-dimensional drawings presented on a screen (Figure 2-6) for 22%, 44%, and 100% WWR windows [16]. Complete 100% WWR was the most preferred, questioning other studies' findings in which 20-40% [12, 13], 50%, and 80% [14] were acceptable. The horizontal window was the second most preferred option similar to previous studies, while the round windows were the least preferred, indicating that large-sized and continuous windows were more preferred. Occupants were asked to give reasons behind their preference for windows and the results showed that natural ventilation, sunlight access, and psychological aspects including spaciousness, improving mood, and improving motivation have played a significant role in determining occupants' window preferences compared to observing the view.

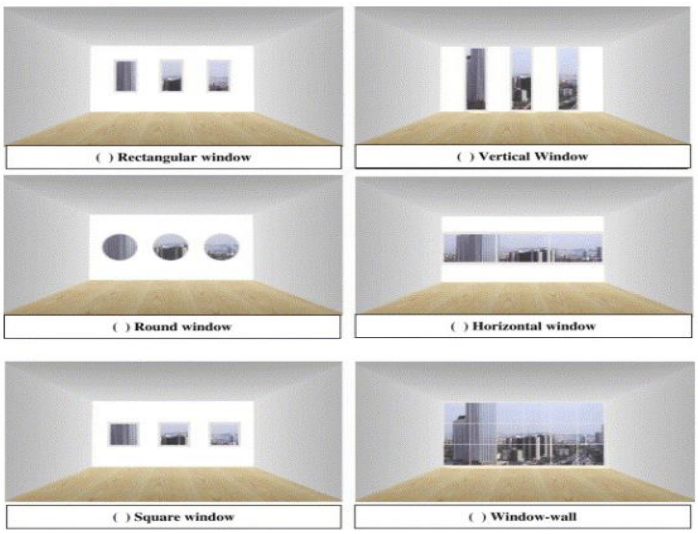


Figure 2-6. The different window-view configurations [16]

The study indicated the importance of the psychological benefit of the view provided separately from its esthetic aspect. However, limitations of previous studies, i.e., the scale of view [12-14, 19] and not considering observer location [12-15, 19], are also found in this study. In addition, under true scale daylight studies, preference for a 100% WWR might not stand as glare and privacy issues might occur.

The previous studies investigated occupants' satisfaction with the amount of view provided by normal non-fractured window-view. Other cases in which the view is distorted or fractured by partitions or shading systems are discussed hereunder.

2.2.2.2 Fractured Views

View fracturing can result from using different numbers of windows or by distorting the view as a result of using mullions, shading, and partitions and can affect view quality. A fragmented view was found to be less satisfactory than a complete one based on a subjective assessment of various layouts with different proportions and mullions' number and width conducted in an early study [19]. The degree to which mullions affected observers' satisfaction was found to be dependent on view distance (i.e., distant views were less preferred when increasing mullions number and width). Other studies indicated that occupants preferred a complete view over a fragmented one, even when the same WWR is provided [15, 16].

This implies that other window design-related factors (e.g., shading devices design and patterns) could affect view quality despite their importance to control glare and thermal comfort issues. Shading devices impact on view quality is usually not considered despite the well-established psychological and physiological benefits of view [9]. Observations of using shading behaviours in office buildings indicated that occupants leave sun shades partially open to preserve a visual connection to the outdoor environment [49], emphasising the need to consider view quality when shading systems are used.

View fracturing by shading and partitions was assessed in the literature [18]. Pleasantness, satisfaction with the view, and visual comfort were investigated with different view quantity shown in Figure 2-7. In the experiment, participants were asked to rate different high dynamic range (HDR) images of the spaces displayed on HDR screen, which can produce images with realistic luminance and ensure control over daylight changing factors [50]. Subjective ratings were correlated with three characteristics: relative view size (the ratio of total pixels that represented a see-through glazed area to the most open scene); average luminance (cd/m^2); and log (maximum luminance/minimum luminance). Results indicated that the increase in all three characteristics is positively related to pleasantness and satisfaction with the view and visual comfort. However, for average luminance and relative view size, all the curves were non-linear, flattening off around 50-60% WWR view size and at 175 cd/m^2 average luminance, indicating a limit to the increases. This indicates that introducing realistic luminance values has affected preferred view size, contradicting the previous result of 100% WWR preference observed on monitor screen [16].

The study indicated that the occupants preferred bright-non glaring spaces and those with a degree of uniformity but not too uniform; a scene with horizontal blinds increased the amount of view and produced a brighter ceiling, non-uniform lit space, and scenes free of glare had higher preference ratings than closed blinds scenes. This, indicates the need for non-monotonous environments (previously discussed in section 2.1).

Figure 2-7. Twelve images rated by participants with different view size and lighting conditions [18]

Nevertheless, the interest in view content was not considered, and view assessment was conducted while subjects were observing 2- dimensional images on a screen which again highlights the scale, depth, room proportions, and fixed position of observer issues, which cannot be assessed with such display method. Additionally, the degree to which view from shading is acceptable in terms of providing connection and sense of relief was not considered nor view preference was assessed objectively.

An attempt to quantify available view from shading systems was conducted in a study to examine different slat shapes in order to maximise occupant's access to external view in healthcare environment [51]. The exposure to external view was expressed as External View Factor (a weighted factor that calculates the number of rays of vision that extend from the patient's eye to the outside through a window opening [52]). The results indicated that flat or gently curved slat shapes showed better results for external view exposure. However, results were not verified in terms of connection to the outdoor with different view contents using human subjects, as they were merely concluded based on calculations.

View clarity from fabric shading was assessed in the literature [45]. Fourteen different types of fabric shadings with different colour and transparency were assessed via subjective ratings and objective responses on the clarity of view. The experiment was conducted in two identical test rooms (see Figure 2-8) from two observing distances from the windows (1.00 m and 2.40 m), under sunny and cloudy weathers seen from a 60% WWR window. Different shades were applied in each room and six visual targets with modified Landolt-C charts were fixed on a fence outdoors at a distance of 4.50 m from the windows, in order to objectively assess view clarity. Visual clarity was subjectively assessed in terms of provided sky conditions, colour vividness, and overall visual comfort; and objectively by counting Landolt-C symbols seen through the shading.

Figure 2-8. (a) Exterior view of test offices (left), (b) interior partitioning (middle), and (c) Landolt C boards installed outside (right) [45].

Shading optical properties affecting the view clarity were considered including the fabric openness factor (OF) (refers to how much is seen through the shade, the weave density, and the direct light transmission); the visible transmittance (T_v) (refers to the percentage of visible light transmitted through the fabric and, indirectly, related to its openness factor and colour); and visible reflectance (R_v) which is related to contrast. The results indicated that OF, T_v, and colour R_v contributed to view clarity score, and that dark-coloured shadings were best ranked followed by grey-coloured ones, despite the different optical characteristics, while the white-coloured shades with small OF had the lowest scores. Sky conditions and distance from the window significantly affected view clarity scores; cloudy sky and longer distance achieved higher view clarity scores. Accordingly, View Clarity Index was developed to assess different shadings with viewing distances up to 2.50 m.

The study highlighted the significance of considering subjective assessment when shading systems are developed as it affects their view perception. Nevertheless, apart from view clarity, connection to the outdoor to provide restoration was not considered. The study was limited to open views only, obstructed views with dense buildings or by natural element were not considered which was found to affect occupants assessment of fractured view [8].

Visual clarity index was applied in a following study to assess window performance based on lighting energy performance and the clarity of view with different seating orientation within the room to optimise the design of roller shades [53]. While Visual clarity index was developed via subjective investigations in the previous study [45], the study stated that “the acceptable ranges of the amount of view are still unclear and the extent in which the distance from a window affects the satisfaction of occupants, if the whole window is still within the visual field, is yet to be investigated, along with the extent of compromise a partly shaded window can cause to the sensation of connection to the outside, even with a very high visual clarity index fabric” [53].

In the literature, energy consumption, heating, cooling, ventilation, and lighting energy loads are usually considered for window design optimisation [23, 54, 55]; whereas for visual comfort, window optimisation is often performed based on indoor illuminance levels, illuminance uniformity, and glare criteria [56, 57]. However, the connection to the outdoors provided by the view from the window is either neglected or considered by performing calculations of the amount of available view [51, 58], as discussed above, despite being a critical factor contributing to occupants' well-being and satisfaction with the indoor environment [2, 3, 40, 43, 59]. The amount of provided view through shading might not guarantee an adequate view, as view quality is not considered.

Other factors related to the dynamic aspect of view (observer related factors) are discussed in the following section.

2.2.3 Dynamic Criteria of Window View

The dynamic criterion relates the observer's viewing position to window view, which changes the amount of view that is visible or blocked by adjacent walls [8]. In a survey-study on view preference, people's satisfaction with the view was found to be related to the distance from the window; the longer the distance was, the more they desired to sit closer to a window [8]. The study discussed that with increasing distance from windows, the view appears as a picture on the wall framed by the window frame, and no longer seen as 3-dimensional reality.

Few studies were found on window proximity impact on occupant's performance and well-being and were studied in relation to the presence of sun-patches within the room [60-62] not considering the view perception parameter. Since view is transmitted by daylight, the studies were considered relevant.

In one study [61], window size and sunlight penetration impact on occupants' emotional response and degree of satisfaction was studied in a typical size office room using two seating positions: frontal and lateral to the window (Figure 2-9). The tested WWR ranged from 10% to 60%; for each window size, the sunlit area on the floor was measured while maintaining indoor thermal conditions constant during the experiment. Subjects were given a proofreading task followed by rating their emotional response in terms of pleasure, arousal, and dominance, in addition to their overall satisfaction with the office environment. The results indicated that in the frontal position, neither the change in the amount of sunlight nor the change in window size had affected the degree of satisfaction, while in the lateral position, the amount of sunlight showed a significant effect on pleasure; the highest level was found with sunlight patches between 15% and 20%, and rapidly decreased when sunlight patch size exceeded 40% causing distress feelings.

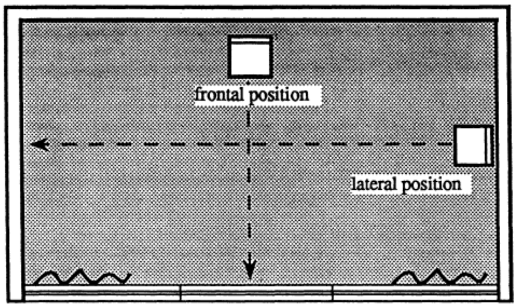


Figure 2-9. Floor plan of the test room with two positions of the observers [61]

The study was limited to two positions and view content was not considered; however, the need to consider viewers' position in daylight studies was highlighted as it was found to be affecting their window size preference and emotional status.

In a similar two part research study [60, 62], more seating positions were investigated to assess the impact of the distance to the sun-patch on the floor on occupants' behavioural responses measured by occupants' performance and seating preference. The study was conducted in a 6.2 m × 4.9 m room with 20–25% sun-patchs on the floor controlled by blinds, and seats were allocated in ten locations in the room where light from the window came always from the left-hand side (Figure 2-9); the preferred position according to the literature [61]. Subjects were asked to complete two cognitive tasks, to place furniture on floor plans based on their preference, and to report their mood in terms of positive and negative affects before and after task performance.

The collected plans indicated that 19% of subjects placed the work desk in the sun patch, 18% preferred to be close to the sun and in the middle of the room, and 21% chose a position sideways to the window but away from the door. The most frequent reasons behind these preferences were visual comfort, control over the room, and window view. Regarding seating orientation, 28% of subjects chose to face the entire room, 18% preferred to face the outdoors through the window, and 32% wanted a view of both to get an outdoor view and to have a sense of control.

As for cognitive performance, the analysis showed no relationships between subjects' performance and their distance to the sun patch; however, some positions were found to significantly impact cognitive performance (independent from sun patch) as shown in Figure 2-10; suggesting other factors affecting the performance.

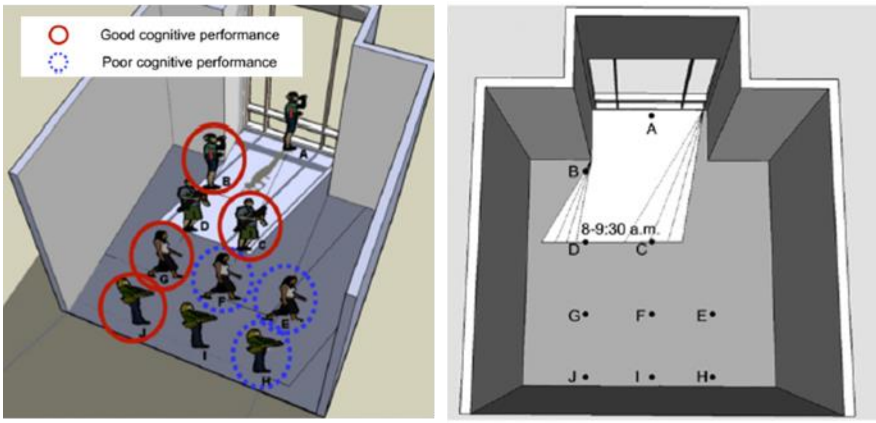


Figure 2-10. (Left) the location of the 20–25% sunlight patch and subjects seating positions during the experiment; (right) Optimal zone for improved cognitive performance [57].

After the task performance, the mood of the subjects in positions close to the sun patch with a better outdoor view (B, C, and D) decreased less than positions far from the sunlight and the window (E, H, and I). Position A, in the sun and next to the window, experienced a higher degree of mood decrease which was explained by the extreme amount of sunlight. The result of seating preferences supported the fact that room occupants are attracted to sunlight and outdoor view in a work environment; yet, people do not always perform better when sitting close to sunlight and a window.

The study was limited to one window size, one view, and direct sunlight, and due to the experimental design, 10 results were obtained for each seating position which might affect the robustness of the results. However, the study underlined the importance of visual massage (view) transmitted by the daylight over levels of illuminance provided for seating position preference, performance, and mood, and also indicated the importance of control provided by the seating position.

In a reduced scale model study [12], satisfaction with a given size of a window was not related to the angle of viewing, i.e., at an oblique angle where the solid angle was substantially reduced, satisfaction remained equal to that from normal incidence viewing. However, increased distance from windows was related to increased preferred window width.

This dynamic criterion of visual perception for relative positions of objects is known as movement parallax [63-65]. As a result, window-view relationship changes and objects at different locations within the view change their relative position when an observer changes their viewing position. Change in distance from the window results in relative changes, whereby at closer viewing positions, the window area appears larger and more content is visible. The view content also appears larger, since more distant objects occupy smaller angles across the retina than closer objects; thus, relatively appear smaller when further away [64, 66]. This reduction in relative size is not linear; i.e., as the distance from the observer increases, change in relative size will occur with smaller magnitudes for the same displacement [66]. When an observer is positioned further away from the window, the aperture appears smaller and parts of the view in relation to the aperture edges cannot be seen, which are usually the most informative parts of the view providing information about the outdoor (i.e., the sky and the ground) [8]. This loss in visual information could offset the benefits of the view, implying that a good, informative, and satisfying view could impose limitations on recommended rooms depth for a given WWR.

The reviewed studies on the dynamic aspect of view underlined the impact of the observer's distance from the window on their subjective preference. However, the actual impact of view presence within the visual field of occupants is not considered, which might affect the psychological benefits of view. In addition, the extent to which the distance from windows can affect occupants' preference, performance, and well-being was not considered. No systematic study was found to investigate occupants' different positions within a true scale room in relation to view perception in terms of quantity; i.e., amount of view within the visual field, associated content quality of view as a result of the dynamic aspect of view considering different distances from windows or different floors locations.

In addition to reviewing research on view perception, the view out standards were reviewed and are presented hereunder.

2.2.4 Views in Sustainable Building Rating Systems

In addition to the building design criteria for indoor luminous environment, view out in sustainable building rating systems was found to be accredited in five prominent sustainable rating systems: BREEAM [67], LEED [68], GREEN STAR NZ [69], CASBEE [70], and HK-BEAM [71]. The view out standards in those rating systems were reviewed and summarised in Table 2-2.

Table 2-2. View standards in sustainable buildings rating systems [67-71]

Rating System	View Criteria	View parameter
LEED	Provide a clear image of the exterior (i.e., view glazing not to be obstructed by frits, fibres, patterned glazing, or added tints that distort colour balance).	View clarity
	75% of all regularly occupied floor area must have at least two of the following four types of views:	View per floor area
	• Multiple lines of sight to vision glazing in different directions at least 90 degrees apart.	Lines of sight
	• Views that include at least two of the following: (a) flora, fauna, or sky; (b) movement; and (c) objects at least (7.5 m) from the exterior of the glazing.	View content
	• Unobstructed views located within the distance of three times the head height of the vision glazing.	View window interior distance
	• Views with a view factor of 3 or greater out of 10 (i.e., the size of view of the outside that the employee has from anywhere in his or her workstation).	View size
	• Long distance views to reduce eye strain for building occupants by allowing the eye to refocus.	View distance from window
GREEN STAR NZ	The distance to the nearest vision glazing is to be no more than 8 m.	View window interior distance
	Brighter areas with some movement are generally more visually attractive although care must be taken to ensure the view is not too distracting.	View content
CASBEE	Windows provide sufficient awareness of the outside environment.	View content
HC-BEAM	At least 60% of all workstations or seating to have a direct line of sight to external vision glazing or a naturally lit internal courtyard or atrium.	View per number of workstations
BREEAM	Adequate view out (a view of a landscape or buildings rather than just the sky) or to be an internal view as long as it is 10 m away from the window to allow the eye to rest.	View content
	95% of their floor area to be within 8 m of an external wall that has a window or opening that provides an adequate view out.	View per floor area
	The window or opening must be ≥ 20% of the wall area.	View size to wall area

	The distance between each window and nearest external solid object (i.e., buildings, screens, walls, or fences) is ≥ 10 m.	View distance from window

All reviewed systems have included view in their rating systems for sustainable buildings; however, view quality criteria are still vague, and the definition of view criteria is different among the different rating systems. For the LEED rating system, although it is the most elaborate, it is not obligatory to attain all view criteria in order to get the credit, which leads to less view quality provided.

For the distance of solid objects from the window, it was defined by a minimum distance of 7.5 m, 8 m, and 10 m in LEED, GREEN STARS, and BREEAM, respectively. View content, on the other hand, is not clearly defined and this is probably due to the difficulty to quantify the view quality; although some aspects of view contents proved to be affecting view preference, such as naturalness and horizontal stratification [2, 5, 6, 10, 11]. In addition, despite the evidence in the literature that view satisfaction is related to the dimensions of the window instead of the window to wall ratio [12, 13, 15, 19], this was not considered in BREEAM standards when minimum WWR was determined. In the remaining standards, the minimum window size was not given.

Based on this review of sustainable building rating systems, it becomes clear that there is a need to be more attentive toward view criteria. The view quality criteria should be appropriately elaborated in order to be applicable to attain their psychological and physiological benefits contributing to occupants' health and well-being. Although the standards and green building rating systems acknowledge the importance of view as part of the visual comfort of occupants and their overall well-being, their impact on occupant performance and productivity is not awarded.

2.3 View Perception Assessment Methods

In the reviewed studies on view perception, people were asked to generally state their satisfaction with view quantity [12-16, 18, 19] and to self-report their stress status [26, 28] in view quality studies about the restorative benefit of natural views, or simply to rate the view as good or bad in other studies [2]. Thus, a comprehensive subjective questionnaire on view perception is needed.

Based on the reviewed studies, occupants of working environments are subjected to stresses for different reasons; one of them is being a disconnection from the outdoor environment (i.e., in windowless environments or when the window is not seen due to the office furniture arrangement and partitions). Moreover, it was suggested by different studies that distance from the window makes people want a larger window for the same WWR. Accordingly, occupants perceive the view to the outdoor differently and might not get the psychological benefits of the view due to the parallax effect, as different view content and different view amount within the field of view can be seen from different locations within the room, particularly in deep part plan offices. Besides stresses resulting from disconnection from the outdoor environment, occupants psychological and physiological status during task performance can be affected by different views perceived within the room. Thus, in order to quantify the view perception, stress-recovery assessment methods could be used including subjective and objective responses.

According to the literature [33], the psychological benefits of view include access to environmental information, access to sensory change, connection to the world outside, and restoration and recovery. The latter is well developed and mainly stresses the impact of nature on reducing stress. The mechanism underlying the stress recovery was explained in two psychological theories, namely attention restoration theory [41] and affective response theory [29].

According to attention restoration theory, when a person is immersed and interacting with a surrounding environment that contains fascinating stimuli, the stimuli modestly promote 'involuntary' capture attention which allow active internal mechanisms responsible for directed attention to recover [41]. Natural environments contain various stimuli that modestly capture attention (e.g., leaves swaying with the wind, birds and leaves sounds, and moving clouds), which require attention that can easily be disconnected from, allowing attention to move between two stimuli and eventually recover. On the other hand, urban environments contain bright lights, vehicles, and construction noise that intensely capture attention; thus, directed attention mechanisms are challenged in order to disconnect from the stimuli producing less restorative environments. The theory explains the differences between natural versus urban environments exposure through a level of cognitive engagement.

Affective response theory states that a person's initial response to engagement within an environment is affective instead of cognitive, proposing that the stimuli prompt an autonomic affective response and that stimuli seen outside of nature context are more threatening, and accordingly, more physiologically arousing**.** Thus, while replacement of directed attention mechanisms is believed to be the source of restoration in attention restoration theory, this theory suggests that the initial autonomic affective response to an environment, forms the following cognitive events.

I.e., if the affective response is positive (such as exposing to nature), the following cognitive and physiological events will be also positive; i.e., as the negative emotions and thoughts are being suppressed, higher levels of positive emotion affect and ability to sustain attention, and reduced levels of negative affect and stress result [72]. This theory has been used to explain the preference of natural environments over those with urban (built) content. Both theories indicate that when the perceived impression of a stimulus is positive, the following cognitive and physiological reactions induced are also positive. Accordingly, this increases the ability to sustain attention, reduces levels of negative affect, and reduces physiological stress [72].

Another model that relates features of the environment and stress can be found in the Circumplex model of affect [73]. Environments that provide high arousal and low pleasure can lead to high levels of stress, while high pleasure and lower arousal environments promote relaxation [61, 74, 75]. Lower arousal and pleasure levels result in a perception of dullness (i.e., less stimulating environment) [76].

Thus, providing views from windows can decrease the stress via providing restorative benefits for occupants [26, 28, 29] by increasing the positive affect in the environment that helps to reduce the stress or providing alternative stimuli to capture attention away from the stressful stimuli. Providing a positive mood for subjects was found to be positively affecting their attention and cognition [74, 77, 78].

Because view has a profound influence on both the psychological (i.e., subjective ratings that appraise the visual content) and physiological (i.e., levels of stress) when a window is observed by an occupant, a multi-criteria approach that includes both types of measures is needed to quantify the differences in view perception. This should be adopted along with preference questions on view perception to provide a comprehensive view quantifying method. Subjective and objective assessment methods that could be used are discussed hereunder.

2.3.1 Subjective and Psychological Assessment

When the environmental stimulus is not strong enough, people cannot clearly recognise the complex interaction between themselves and that stimulus; generally, people are not sensitive to their visual environment unless it is bad [79], and when the minimum comfort requirements are met, people may not be able to specify different degrees of comfort with great accuracy, and it is always easier for people to differentiate between satisfactory and unsatisfactory views than being able to distinguish the degrees of satisfaction [62].

Therefore, it is important to measure how view perception affects people's mood and well-being while assessing their general preferences. Nevertheless, in order to acquire more accurate measurement of stress in relation to a visual stimulus (i.e., view), the use of mood scales can be a more accurate form of subjective assessment than general reported well-being, as people's reaction to their perception of the environmental stimuli can result in a mood change which will eventually affect their behaviour and productivity particularly in short-term experiments, in which occupants [33] will not always acquire a precise understanding of stimuli directly by their perception [60].

Thus, measurement of mental processes, that can only be reported by the person, can be examined via mood variations in different conditions as the mood mediates environment and human behaviour and, consequently, affects the process that people use to formulate their judgment and evaluations [80]. Since subjective assessment used in view preference studies was merely general questions about observers' degree of satisfaction with the view, more comprehensive approach that assesses view quality based on its impact on view quality perception and on occupants' stress reduction and consequently their psychological well-being is needed.

Several validated questionnaires can be used to assess subjective stress which utilises detailed questions about observers' mood or distress to truly reflect the impact of view on their health and well-being [11] including the A-State anxiety test [81], Zuckerman Inventory of Personal Reactions (ZIPERS) [82], and Positive and Negative Affect Schedule (PANAS) [83].

The A-State anxiety test is a well-known questionnaire to subjectively assess psychological stress in different environments, in which 20 questions are used for people to report their current affect (e.g., I feel calm, I feel secure, etc.) on a 4-point scale ranging from, "Not at all" (= 1) to "Very much so" (= 4). "Its occurrence and intensity are mainly related to a person's cognitive response that corresponds to the stressful and nervous feelings caused by certain stimuli" [11].

The Zuckerman Inventory of Personal Reactions (ZIPERS) [74], has been used in previous studies on restorative effects of nature and found to be a reliable measure of restoration [29, 72, 84]. The ZIPERS questionnaire includes several items that measure positive affect (e.g., happiness, friendliness, etc.), negative affect (e.g., anger, sadness, etc.) and attentiveness on a 5-point Likert scale ranging from, "Not at all" (= 1) to "Very much so" (= 5).

Another well-known affect questionnaire is PANAS, in which people rate how they feel using questions separated to positive affects (e.g., interested, excited, etc.) and negative affects (e.g., irritable, nervous, etc.) using a 5-point scale from, "Very slightly" (= 1) to "Extremely" (=5). The PANAS scale has been used broadly in indoor environmental quality research, especially in visual studies [85, 86] to measure fluctuations in mood. Positive affect (PA) reflects enthusiasm, activeness and alertness; a high PA provides a state of high energy and high concentration, while a low PA reflects sadness and exhaustion. On the other hand, negative affect (NA) is an indicator of distress and incorporates aversive mood states, as low NA implies a state of calmness and security [83]. Although all three tests can be used to assess the momentary positive affect (PA) and negative affect (NA) of the observer, PANAS has the advantage of being able to assess these two affective components separately [83] and has been subjected to structural examination more than other measures of well-being [87].

A summary of questions used in literature to subjectively assess the view and the psychological questionnaire that can be used to assess the stress are demonstrated in Table 2-3.

Table 2-3. Subjective evaluations used in literature to assess view quality and well-being

Evaluation Type	Assessment Measures		Scale Type	Scale Range	Ref.
View preference	View size and layout	Rate the satisfaction with the size of the window	Point	1-5	[19, 48]
			Point	0-7	[18]
		Rate the satisfaction with the width and the height of the windows	VAS*	0-10	[15]
		Rate the satisfaction with the positions and shapes and windows			
		Rate the satisfaction with the number of windows			
		Select the preferred number or/ and layout of windows	-	-	[12, 16]

		Select the preferred layout and location	-	-	[13, 19]
	Satisfaction with view content	Rate satisfaction with view provided by the window	Point	0-10	[88]
		Rate the desirability of the window view?	Point	1-10	[47]
	View clarity through shading	Rate the satisfaction with the view clarity and its colour vividness	Point	1-7	[45]
Psychological and mood	ZIPERS	Report the current psychological affect	Point	1-5	[82]
	PANAS			1-5	[83]
	A-State			1-4	[81]

*VAS: Visual Analogue scale (a 10 cm line were participants can mark any value between 0 and 10)

Although the psychological questionnaires are validated, experiments would often use different methods for collecting subjective ratings of view from windows and this may be one reason why studies found inconsistent results as discussed in section 2.1. A validated questionnaire to quantify view quality subjectively is needed which could be developed from existing literature on restorative environmental preference [79-83] and from daylight studies. In addition, it should be noted that mainly relying on subjective ratings, is often prone to methodological biases [17]. Thus, despite its importance, mainly depending on subjective preferences may not be sufficient to evaluate the quality of view, and objective measure to assess view perception is needed, which is discussed in the following section.

2.3.2 Objective Physiological Assessment

Since self-report evaluations are often considered subjective, objective measures are required to validate the findings and to verify the effects of stimuli [89]. The physiological measures are objective, depending on the biological response of the human body and are widely used in visual stimuli-stress studies [11, 29, 90, 91].

Physiological responses towards the surrounding environment can be monitored to detect any change between different conditions, i.e., when different visual stimuli are presented. Physiological responses can be monitored using instruments that provide information on the activity of the measured systems, such as muscle tension, skin temperature, brain waves, skin conductance, blood pressure, and heart rate [92]. Such physiological reactions can identify certain changes in body function and well-being that may be outside the conscious awareness of human beings and hence cannot be identified using verbal and observational measures [93]. Thus, physiological response measures are essential to objectively detect such physiological reactions.

In principle, the Autonomic Nervous System (ANS) is part of the nervous system that regulates key involuntary functions of the body and has two divisions: the Sympathetic Nervous System (SNS), which controls stress, mobilization, and activation; and the Parasympathetic Nervous System (PNS), which is responsible for the relaxation and restoration [94]. The stress was found to be influencing the ANS, consequently, using measures to ANS activity gives insight to physiological stress or recovery status [95].

A wide range of physiological measures has been used in the literature to assess human responses in terms of emotion or stress to reflect ANS activity. Skin conductance (SC), heart rate (HR), and heart rate variability (HRV) measures have been established to assess stress levels in visual research. The three physiological measures purposed and applied in visual research are presented in Table 2-4.

Table 2-4. Physiological measures used in visual or stress related studies

Physiological Measure	Type	Purpose	Application	Ref.
Skin conductance	Phasic skin conductance (SCR)	Reflects changes in arousal associated with short-term events	Investigate restorative effects of nature	[72, 90]

[96]		(discrete environmental stimuli)	Subjective and physiological responses to façade and sunlight pattern geometry in virtual reality	[97]
			Ovserving emotional face task impact on rousal effects	[98]
			Physiological responses to simulated and real environments: A comparison between Photographs, 360 Panoramas, and Virtual Reality	[99]
	Skin conductance level (SCL)	Measures arousing responses to continuous environmental stimuli	Impact of plants on stress and recovery in office environment	[100]
			Detection of stress levels from biosignals measured in virtual reality environments	[95]
			Restorative effects of virtual nature settings	[72]
Heart rate variability (HRV)	Blood volum puls aplmplitude (BVA) [106]	Reflects relative changes in the volume of blood in vessels where increased SNS activity decreasing BVA while increasing PNS increasing BVA	Investigate stress levels for nature, urban, and plants in office environment	[11]
			Psychophysiological responses and restorative values of natural environments presented on screen	[101]
			Stress recovery during exposure to natural and urban vedios	[29]
	Heart rate variability amplitude (HRV_a)	Indicates the variation in duration between two successive heart beats where decreased HRVa indicates stress while increased HRVa is related to lower performance anxiety	Detection of stress levels from biosignals measured in virtual reality environments	[95]
Hreart rate (HR)	Heart beats per minute	Incresed HR indicates stress and lower HR indicates resting or cognitive engagement	Ovserving emotional face task impact on rousal Effects	[98]
			Stress levels detection during computer based task	[102]

	Restorative effects of virtual nature settings	[72]
	Subjective and physiological responses to façade and sunlight pattern geometry in virtual reality	[97]

These signals were selected for their ability to reflect the nervous system activity in terms of stress and recovery with continuous measurement [29, 72, 90, 95, 103-108] and their ability to elicit initial responses for discrete stimulus [94, 95, 99]. In addition, these signals have been used to measure human responses when immersed in virtual reality environments [95, 97, 99], which is proposed as the representation method in this research project.

2.4 View Representation Methods

The methodologies used to evaluate window view can be divided into two categories: those using daylight and real windows, and those using artificial lighting and images that are displayed or projected to simulate the real environment.

When views are assessed in a daylit environment, they have the advantage of providing a realistic scene with the visual depth and accounting for dynamic factors of daylight (i.e., spectral properties of the source, light intensity, etc.) and the visual content (e.g., moving objects, changing elements in the views) as found in several studies [6, 12, 15, 39, 45]. However, only a limited number of views can be examined when windows are tested, and different rooms with comparable conditions may be difficult to locate (i.e., window sizes, number of windows, and room dimensions, etc.,). This causes challenges when comparing the findings between different studies. Also, extraneous variables (e.g., noise, temperature, etc.) cannot be easily controlled when real windows are used, which makes it difficult to isolate the experimental effect.

Conversely, displayed and projected images on the screens overcome the shortage of limited scenes when windows are used, allowing direct control over the light source [6, 7, 11, 13, 14, 16, 18, 19, 39]. However, this method too has its limitations (i.e., it lacks the depth in the view, immersiveness, and the dynamic aspect of view that can change by viewing position within a room; being displayed on 2-dimensional displays). Also, the scale of the viewing room with that view is not considered as the projected or displayed images on screens are not proportional to human scale and may have an influence on people's preference of windows in real conditions. Moreover, some of the aforementioned studies used reduced-scale models with real windows [12] or with projected 2- dimensional screen images [13, 14, 19] to assess the accepted view size, which imposes another limitation on the scale and view size in the visual field that can affect view preference (i.e., visual parallax).

The currently used methods in view preference assessments and their limitations in relation to the current study on view are shown in Table 2-5.

Table 2-5. Summary of view representation methodologies used in previous view studies

			Advantages					Limitations						
Reference	Study Purpose	Method	Controlled lighting conditions	Variety of scenes	Dynamic view	Room proportion	Real scenes (3-dimentional view)	Artificial setting	2-dimentional- static views	Fixed observer position	Scale /view size in field of view	Limited scenes	Light variations	Room proportion not considered or Limited
[13, 14, 19]	View size and position preference	Projected images through aperture in reduced-scale model	√	√				√	√	√	√			√

[12]	View size preference	Reduced-scale model and real view			√		√			√	√	√	√	√
[7]	View and glare	Printed Images placed on simulated artificial window	√	√				√	√	√	√			√
[6, 39]	View interest and glare	Pictures projected from wall aperture on a tracing paper screen	√	√				√	√	√	√			√
[11]	View content preference	Images displayed on monitor screen	√	√				√	√	√	√			√
[18]	View size	Images displayed on high dynamic rang (HDR) screen	√	√				√	√	√	√			√
[15]	View size preference and light distribution	Real views			√	√	√					√	√	√
[16]	Window size and shape	3D simulation displayed on screen	√	√		√		√	√	√	√			
[45]	View clarity	Real views			√	√	√					√	√	√

Another approach is the use of virtual reality (VR), which allows the visualisation and evaluation of the dynamic environments. This may overcome some of the challenges described when using the methods that were outlined in Table 2-5.

The use of VR technology with VR headsets results in an immersive virtual environment that can be acquired using photography, video filming, or via rendering of virtual modelled environments. VR provides a comparable field of view, interactive viewing mode, and stereoscopy (3- dimensional vision) for the main view direction. In addition, the mobility of VR methods enables the reproducibility and seamless conduction of experiments [48], which can assess in view experiments results in terms of robustness and consistency. As a result of immersiveness, this method minimises the artificial nature of experiments as subjects cannot see the setup (e.g., devices, wires, etc.,) or the experimenter, which might affect subjects' assessment of the surrounding environment. Moreover, this method enables the interaction between the subjects and experimenter as the latter can monitor what subjects are observing.

In addition, in terms of controlling the confounding variables, the VR headsets have the advantage of providing more control of different variables within the surrounding environmental factors (e.g., spatial and geometric design variations) [109]; and personal factors that can affect the experiment's results, as people tend to change their behaviour in the presence of others. Other factors that might affect visual perception and assessment such as temperature, the current weather [110], and noise [111, 112] can be all controlled when conducting the experiment using the VR as the visual stimuli provider.

In view and light perception studies, it allows the control of variation in luminous conditions of unpredictable sky conditions, which is one of the main challenges in experimental studies in daylit environments [15, 48]. This is an important factor in view perception to maintain the same perception of view and surrounding environment to avoid the subjects looking at different luminance levels, which can affect their comfort during the experiment and consequently their assessment of investigated stimuli [15].

Moreover, the rapid change of visual stimuli in a VR environment reduces the time needed to perform the experiment, providing more time for analysing and comparing the research results. The use of VR methodology overcomes the limited views usually available for researchers when real views are used, which makes it difficult to replicate the same experimental setup with a wide range of views with the same surrounding environmental factors; all of which can be resolved using a VR method. Thus, in the VR method, view contents can be studied in a relatively shorter period of time as views are unrestricted to certain geographical locations or climate conditions with unlimited view content.

VR technology provides subjects with stereoscopy vision which provides the depth perception that cannot be obtained when mesoscopic 2-dimensional scenes are assessed [113]. Another key difference between assessing a 2-dimensional and 3-dimensional immersive visual environment is the fact that the visual stimuli can be seen within a comparable field of view [50] (i.e., subjects are immersed in the scene and the visual stimuli are presented in realistic one-to-one scale), providing the interaction between subjects and the presented scene which can greatly improve the realism for user-experience studies [48, 114-116].

In conclusion, VR appears to be an adequate research tool for visual perception studies; thus, it is proposed to be used in assessing view perception in this research. Nevertheless, this method needs to be validated in terms of visual performance and luminous environment perception in comparison to a real environment before being utilised in view studies.

2.5 Critical Summary and Discussion

High-quality views from windows can be achieved via the interaction of several factors, including content-related factors such as naturalness, movement, and horizontal stratification; window design-related factors including shape, size, and fractured views caused by shading devices, mullions and partitions; and dynamic observer-related including eye level and observer distance from the window. The view quantity resulting from the interaction of observer location, window features, and fractured views also affect the view quality provided. Thus, view quality and quantity are interrelated terms as an insufficient amount of view will result in low-quality view, which eventually affects the basic psychological benefits of the window.

View content has been assessed mainly subjectively with only one attempt to assess view content quality based on point rating method [9], which was also based on former subjective ratings. The method gave natural views the highest weight; however, this is not always true as not all natural or urban views are the same. In addition, other factors that may affect view preference, such as colour, weather conditions, movement, and presence of people and living organisms were not considered; hence, other objective measures that can reveal view quality are needed and more view-impacting factors should be considered.

For window aspect ratio, horizontal openings were preferred over other alignments in most of the reviewed studies. However, for preferred view size, results were inconsistent among different studies as some studies found that 35% WWR is acceptable, whilst others preferred large openings up to 100% opening of the wall. This could occur as a result of personal differences and geographical locations, differences related to room proportion and viewer position, or it could be as a drawback of used methodologies (reduced scale models, 2-dimensional view display, and the fixed position of observer). Thus, a new display methodology that overcomes previous limitations is essential.

The impact of shading systems and technologies on view perception (i.e., view perception and connection to the outdoor resulted by fractured views) is still unclear. View quantity was calculated for some of the shading systems; however, its impact on view perception should be assessed with human subjects to understand the amount of view required to sustain connection with the outdoor environment. Furthermore, how critical occupants would be about shading systems with different level of view interest and different view content needs further investigation. In addition, studies on other factors that might affect view perception including the different window design optimising methods (e.g., WWR, smart windows, etc.) have been limited to lighting and energy performance optimisation [22-25], not considering the corresponding view quality perceived through these window systems, and their impact on connection to the outdoor has not been identified yet.

The dynamic aspect of view perception resulting from the interaction between view content, view ratio, viewer position, eye level, and distance from the view is the least investigated. As the distance from the view increases, the amount of omitted information from the view increases and smaller the apparent size of the view within the occupant's visual field. This could limit the psychological and physiological benefits of view, causing distress for occupants by feeling isolated from the outside world, which could affect their productivity, health, and well-being. Furthermore, studies showed that access to view is one of the main reasons behind occupants positioning and orienting their work desks, suggesting a strong connection between view perception and providing satisfying working environments that can affect occupants' performance and well-being. However, no systematic study was found to investigate occupant's position within a room impact on view perception; thus, more studies are needed on this regard.

Table 2-6 summarizes the investigated aspects on view perception, their results, and their relation to occupant's location, performance, preference, and well-being.

Table 2-6. Summary of the results on view quality parameters

Quality factor	Content	Design related factors					
		Shape	Size	Fabric shading	Slat shading	Mullions	Partitions

Results	View content quality point system [9] Natural views are preferred over built views [7, 11, 26, 27, 29, 42]	Rectangular window with horizontal alignment is preferred [12, 13, 19]	Minimum accepted window size (2.10 m ×2.10 m) [12] 25-30% WWR [19] Between 50 and 80% WWR [14] 100 % WWR [16] 40% WWR [15]	Dark-coloured shadings with high opening factor and high visible transmittance were preferred [45]	Flat or gently curved slat shapes showed better results for external view exposure [52]	Depends on the view distance, i.e. distant views were less preferred when increasing mullions number and width [19] A complete view is preferred over a fragmented one, even when the same WWR is provided [15, 16]	50-60% relative view size [18] Larger view angular size from working cubicle is preferred [40]
Relation to Subjective preference (satisfaction)	√	√	√	√	×	√	√
Relation to occupants' location within the room	×	×	Rear and side viewing position in one study [12]	For 1.0 m and 2.4 m away from window [45]	×	×	×
Relation to occupants' performance	Partially/ for naturalness vs man-made enhanced performance found with natural views [40, 42]	×	×	×	×	×	More vegetation and larger view angular size enhanced performanc e [40]
Relation on mood and well-being	Partially investigated for natural over man-made views [11, 29]	×	×	×	×	×	High level of reported fatigue associated with lack of window view [40]

The reviewed studies clearly illustrate the need to quantify view using a method that would reveal reasons for view preference, and account for different design factors' impact on both psychological and physiological responses. This is important for window design optimisation in order to provide a holistic analysis of window performance.

Studies on view perception through window performance systems (e.g., shading) are minimal (i.e., the impact of shading systems on users' perceptions of view is not well understood) as the amount of view seen from such systems has been assessed based on geometrical calculations [45, 51, 53]. The shading devices colours and design and their impact on view perception should be investigated while accounting for different view contents.

When it comes to view quality assessment and its impact on building occupants, the current body of research relies heavily on subjective assessment of satisfaction with view [6, 7, 12-15, 19, 26, 28, 30, 39, 44], and quality of view was mainly assessed based on provided content in terms of naturalness compared to urban views. Moreover, view content and size have been examined while neglecting task performance in the investigations indicated in Table 2-7. Objective assessment using physiological measures or memory tasks were considered to confirm the higher quality of nature over the built views using physiological or task performance; however, these measures were not used to assess view quantity or other view contents (i.e., different levels of built and nature elements).

Table 2-7. Reviewed studies limitation regarding assessment methods and view investigated parameters

The investigated parameter		Response measures	Assessment method	Task performed	Ref.
Content	Nature vs. man-made views	Recovery time in healthcare	Objective	×	[27]
		Self-reported stress	Subjective	×	[26]
		Self-reported stress biofeedback	Subjective Objective	×	[11, 29]
		Self-ratings on view preference	Subjective	×	[7]

		Tests that requires concentration Digit Span Forward and Backward tests	Objective	√	[42]
	Naturalness and horizontal stratification	Self-ratings on view preference	Subjective	×	[6]
	View's complexity, coherence, legibility, and mystery	Self-ratings on view preference	Subjective	×	[39]
Content and quantity	window size, distance of the view, and view content	Outcome of student performance in schools	Objective	√	[43]
	View naturalness Size of view	Self-reported fatigue Workers performance	subjective Objective	√	[40]
	Acceptable minimum window width	Subjective using questioner	Subjective	×	[12]
	Window size, mullions no. and width	Subjective using questioner	Subjective	×	[13, 19]
	Window size, and proportions	Subjective using questioner	Subjective	×	[14]
Quantity	Fabric shading view factor	Subjective using questioner with objective visual clarity test through shading	Subjective Objective	×	[45, 53]
	Window size based on the function of the room	Subjective using questioner	Subjective	×	[44]
	Window number and size	Subjective using questioner	Subjective	×	[15]
	View size	Self-ratings on satisfactions with size	Subjective	×	[18, 48]
	Window size and shape	Subjective using questioner	Subjective	×	[16]

Studies on the quantity of view indicated that people have reported the preferred size of the window while looking directly to the view. However, under working conditions where people are performing tasks, the view could be partially within the field of view instead of being completely seen. The impact of the amounts of view within the visual field when occupants are performing tasks at different distances from the window on occupants' health and well-being is not well understood.

The preference to set closer to window view was assessed using general questions on occupants' satisfaction without task performance during the experiment, which can affect stress levels and reported view preference and mood. In addition, the proximity to window preference under different view content, climate, or cultural differences was not considered. Other interior conditions impact on view distance, such as the privacy, social interaction, in addition to thermal and lighting comfort interaction with views, is not well developed.

Neither the amount of view within a visual field that provides connection to the outdoor nor a comprehensive method to quantify it are given in literature despite their possible impact on room-window design, partitions, seating position distribution, and on technologies and smart window designs that are being developed to account for glare, thermal comfort, and energy consumption issues.

2.6 Conclusion and Research Flow

The reviewed literature in this research clearly demonstrated the need to investigate the view quantity parameters and their impact on view quality perceived.

Subjective measures including occupants' perception, preference, and performance, are important markers of indoor environmental quality. Many studies have underlined the importance of occupants' position to window, and they concluded that window proximity is related to occupants' satisfaction [8, 26, 117, 118] and others highlighted views impact on occupants' health and well-being [11, 26-29]. However, few studies considered the distance from view impact of on occupants' mood, performance and preference, despite the fact that access to outdoor view was established as one of the main reasons behind people selecting their seating positions and orientation, indicating the importance to access views.

The sufficient amount of view and the extent to which the different observers' position in relation to window view affects their perception of the view are still unclear. The impact of view when the whole or part of the window is within the visual field of view while working is yet to be investigated; attempting to understand the causal relationships between viewer position and view perception. In addition, studies have reported different preferred window sizes which might be due to the view representation method used, or the heavily relying on subjective responses in such research.

Consequently, in order to attain more robust conclusions on view perception, a more comprehensive methodology to assess view quality, affected by view quantity, and a new representation method that replicates the visual properties of real environments is needed. This research aims to develop a refined comprehensive methodology to quantify view perception in the office environment. A systematic experimental approach was adopted to address the above-discussed gaps by developing an alternative visual representation method that can reflect the luminous characteristics of a real environment, and by developing a comprehensive subjective and objective evaluation method to quantify view perception. An overview of the methodology and studies conducted to attain this aim are presented in the following chapter.

Chapter 3

Methodology and Experiments Overview

3.1 Introduction

This chapter describes the methodological steps developed in the different phases of this work and introduces the different studies conducted during this course of work, which are presented in four papers presented at the end of the thesis. In the first phase (paper 1), an alternative virtual visual medium that replicates the luminous characteristics of real environment was developed. An experiment was conducted to validate its ability to reflect similar characteristics of real luminous environments (i.e., perceived similarly), in order to be utilised as a visual representation tool in view perception studies. In the second phase, a comprehensive method to quantify view perception was developed using extensive subjective and objective (physiological) responses. This method was used to collect data in two case studies: variations in view perception due to changing the viewing position (paper 2) and variations in view perception as a result of changing the window size (paper 3). The data collected in the latter study was assessed against energy and daylighting performance of windows with different size, aiming to optimise window size for view perception, energy, and daylighting for a holistic window performance assessment. Finally, the methodology developed to quantify view quality was revised. The designed questionnaire on view perception was assessed for reliability and the relationship between subjective and objective data was investigated using correlation analyses to provide a refined methodology to quantify view quality.

3.2 Test Room

In this course of work, a real office room located in Energy Technology Building, The University of Nottingham, UK was used to replicate in virtual reality an environment that was used in the different experiments. The room had internal dimensions of 4.35 m x 2.85 m and internal ceiling height of 3.2 m. The internal walls of the room had the following reflectance properties: $\rho_{wall} \approx 0.7$, $\rho_{floor} \approx 0.1$, $\rho_{ceilin} \approx 0.8$. The window was closed and manipulated in size using matt white paper with similar reflectance properties of the walls $\rho_{paper} \approx 0.7$. The reflectance properties were estimated using the colour of walls, floor, and ceiling and the Munsell value, as per Equation (3-1) [119].

$$\rho \approx \frac{(Munsell\ Value \cdot (Munsell\ Value - 1))}{100} \qquad \text{Equation (3-1)}$$

The room had slight colour variety and was equipped with office furniture to resemble a simple office working environment. Tasks were mounted on the wall and rotating chair was placed 1.50 m from the task wall so the eye level of 1.20 m was perpendicular to the middle of the task. This room was used to validate the use of VR in the first experiment. Afterwards, it was used as the environment replicated in VR with different levels of window view in the following two experiments on view perception.

3.3 Experiments Overview

Three laboratory studies were conducted during this research aiming to develop a valid methodology to quantify view quality. Each of the three experiments had a different sample (i.e., different participants) who took part in the experiments and the experiments were conducted on separate periods of time during the study timeline.

The first experiment was conducted to develop and validate an innovative VR method to be used as a representation method in visual perception studies (i.e., view perception in this research). The second and third experiments were performed as two case studies to collect data on view perception using a proposed method to quantify the view quality by its restorativeness (i.e., its impact on recovering from stress). Using the VR office, the first case study investigated the variances in view perception due to change in observer location, while the second case study investigated view perception from different window sizes. In a complementary study, the results obtained from the second case study on view perception were assessed in relation to simulated daylight and energy performance to provide a holistic approach to assess window design. Finally, subjective and objective responses collected from the two case studies were further used for reliability and correlation statistical tests to provide a refined methodology to quantify view quality. An overview of the experiments is provided in Figure 3-1.

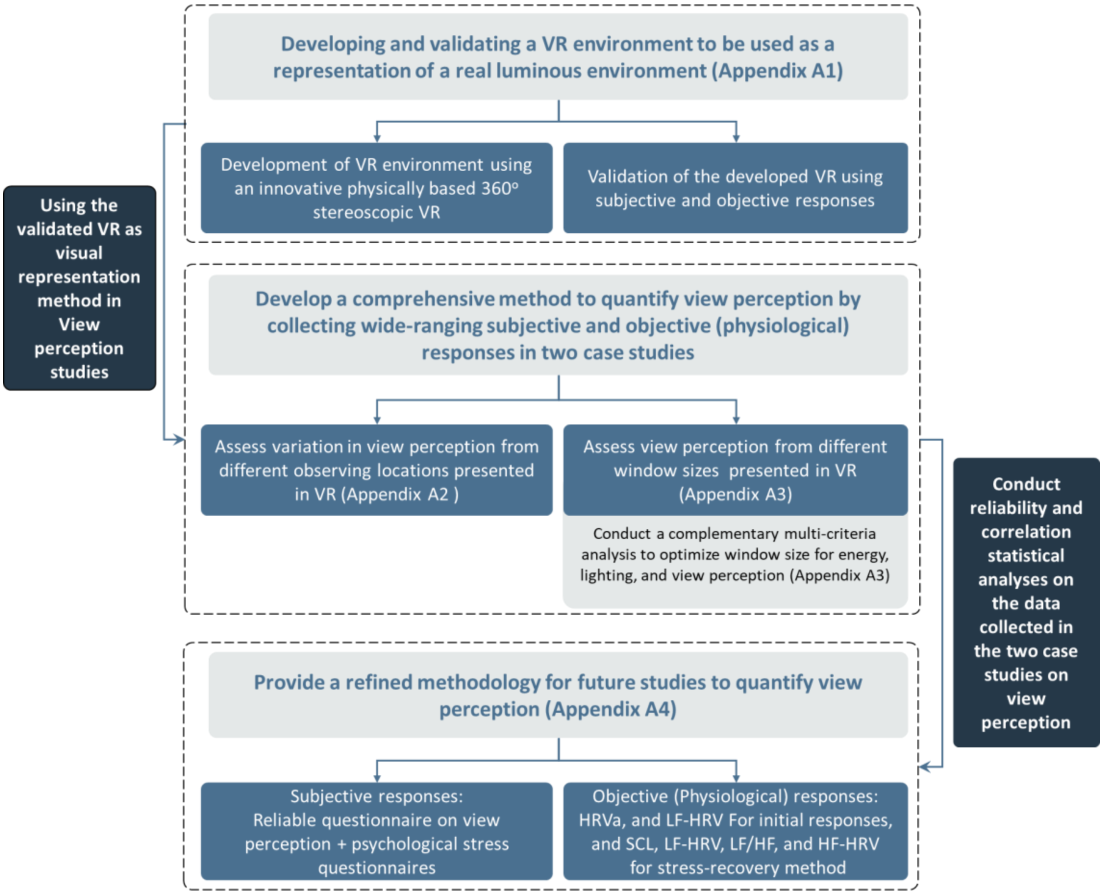


Figure 3-1. An overview of the experiments conducted during this research

The work conducted in this research has led to four journal papers presented at the end of this thesis (appendices A1-A4). A summary of each paper providing an overview of the different stages conducted during the research is provided in the following sections.

3.3.1 Paper 1: Developing and Validating VR for Visual Perception

As discussed in section 2.4, the methodologies used to evaluate window views can be divided into two categories: those using daylight and real windows, and those using artificial lighting and images that are displayed or projected on 2-dimensional screens to simulate the real environments.

When reduced scale models are used in both real and projected 2-dimensional images, the limitations of unrealistic scale and the view size in the visual field are introduced. When views are being assessed from windows, they have the advantage of providing realistic views with depth and dynamic factors; however, only limited scenes can be examined from the same window and only one room with the same ambient conditions can be used, which will affect consistency of the experimental results and robustness. Also, the uncontrolled fluctuations in the outdoor view lighting and view content besides other extraneous variables (e.g., noise, temperature, etc.) would make it difficult to isolate the effect when different trials are required.

Alternatively, displayed and projected images on screens overcome the shortage of limited scenes in real window studies and light fluctuations, yet, they lack the depth in the view, immersiveness, and the dynamic aspect of view (i.e., changes in view seen from different viewing locations within a room); being displayed on two dimensional displays. Also, the scale of viewing room is not considered as screen displayed images are not comparable to human scale and may have an influence on people's preference of windows in real conditions.

Table 2-5 showed that the existing methods have limitations that could be overcome when the VR is used. The literature suggests that a VR immersive environment could be used as a representative method to study luminous environments in terms of scale, immersiveness, and controlled luminous conditions. However, these factors should first be assessed to validate the use of this technology when compared against real visual environment. The few studies that existed in this regard and their limitations are discussed in the introduction in Appendix A1. The studies were mainly limited to one aspect of the luminous environment perception such as lighting appearance [120] or high-order perceptions [48]. Also, the studies were either limited to subjective evaluation or lack the physical calibration of the VR content. Visual quality attributes (i.e., colour, contrast, or detail) are yet to be validated. Hence, a replication of the results using photometrically calibrated VR with expanded features of the luminous environment, in addition to objective assessments of visual performance, is required to further confirm the applicability of VR when used to evaluate the luminous conditions of any visual environment, and eventually, in view perception studies.

Accordingly, an experimental study was designed to evaluate the differences in visual perception (subjectively and objectively) under real and virtual reality conditions by comparing a simulated 3-dimensional virtual office developed using physically-based (photometrically calibrated) imaging technique against a real one. Several criteria were used to assess the luminous environment in a more comprehensive approach to include the luminous environment appearance, high-order perceptions, and visual quality. Both settings presented similar physical and luminous conditions to twenty participants (N=20). The subjects volunteered to participate in the test and were recruited from Energy Technologies Building and Engineering

Faculty from the University of Nottingham using online advertisements. Subjects were undergraduate and postgraduate students, 10 males and 10 females with mean age of 26 years (SD= 6.24) and were from different ethnic backgrounds. None of the participants reported any colour vision problems and eight participants wore corrective glasses during the experiment. The experiment lasted for approximately 40 minutes and participants were given a five-minute break between the two conditions. The study was conducted during winter months (November-December) of the second year of the investigation.

The method was validated for use as an alternative medium to represent real visual environments. This was supported by either subjective and/or objective assessments conducted during the experiment, and by participants' interaction with the virtual environment based on measurements of perceived presence. Subjective assessments included questions on luminous environment appearance (brightness, colour-temperature, distribution) and high-order perceptions (pleasantness, interest, spaciousness, excitement, and complexity). Objective assessments used contrast-sensitivity and colour-discrimination tasks to assess visual performance in the real and virtual environments. Results showed no significant differences between the two environments based on the studied parameters, indicating a high level of perceptual accuracy of appearance and high-order perceptions. Even though attributes regarding scene quality (colours, detail, and contrast) were perceived to be significantly different from the real environment, objective tasks showed that similar contrast and colour appearance can be produced in the virtual environment with minor impact on fine-detail due to limited resolution. Virtual reality may be a promising alternative representation medium to investigate visual perceptions (e.g., view perception) as the overall appearance of the scene can still be correctly acquired.

An overview of the experiment indicating the different steps conducted and the experiment workflow are indicated in Figure 3-2. The detailed steps followed to generate the test environments, data collection methods, data analysis, results, and discussion are detailed in appendix A1.

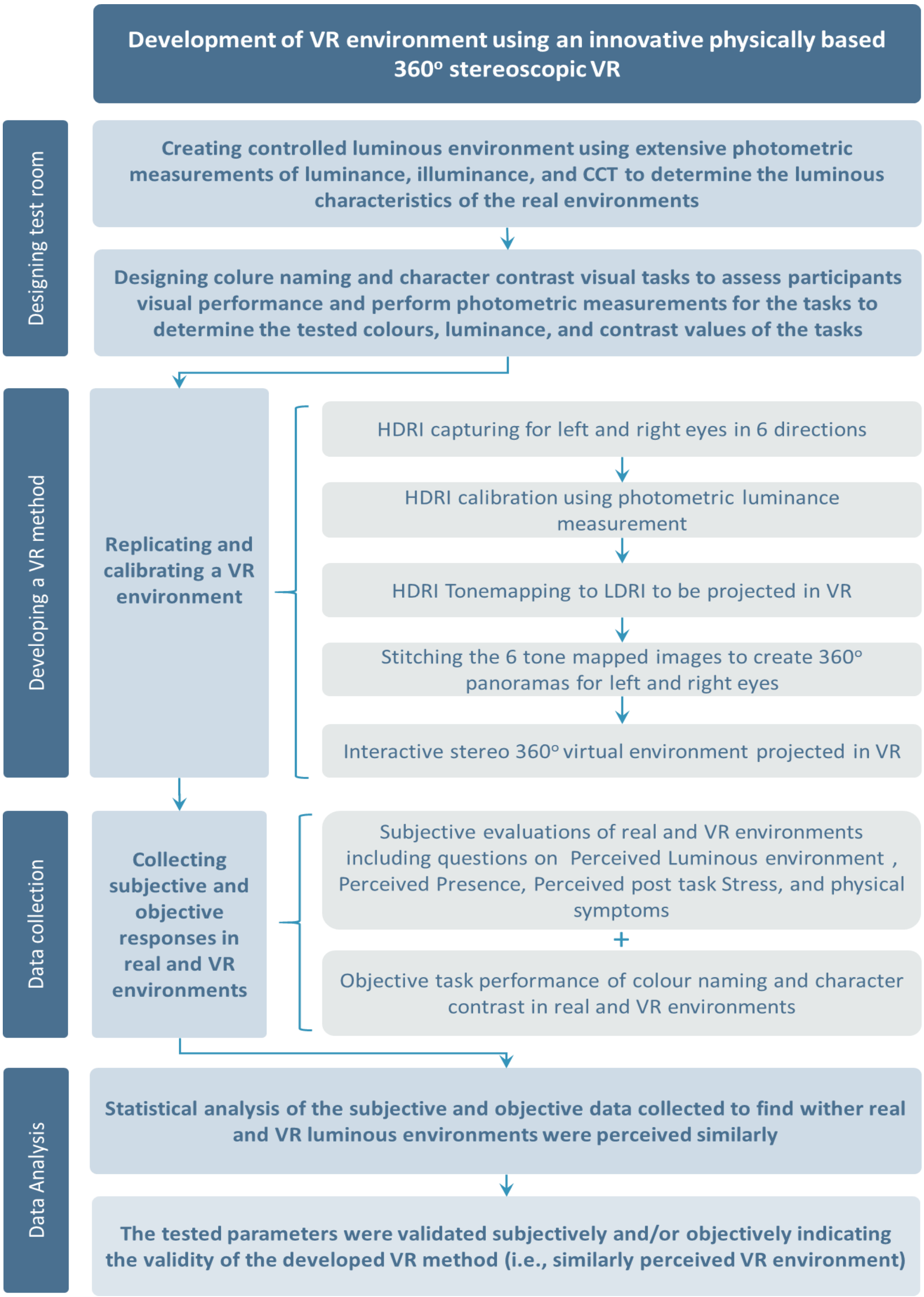


Figure 3-2. An overview of the experiment conducted in the first paper to develop and validate a VR methodology for visual perception studies

3.3.2 Papers 2 and 3: Developing a Comprehensive Method to Quantify View Quality

Providing view from a window can decrease stress by providing restorative benefits for occupants [26, 28, 29]. This works by increasing the positive affect in the environment that helps reduce stress or by providing alternative stimuli to divert their attention away from the stressful stimuli, as discussed in section 2.3. Since view has a profound influence on both physiological (i.e., stress levels) and psychological (i.e., subjective ratings assessing the visual content) when an occupant observes a window, a multi-criteria approach that includes both types of measures was used to quantify differences in view perception. This should be considered along with view preference questions to assess whether a preferred view is a view that provides restorativeness. The method used was developed through conducting two case studies on view perception, where in the second case study, additional subjective and objective measures were used to develop a refined methodology based on the data collected in the two case studies. The experiment procedure was similar in both experiments; however, the conditional variables were different.

To evaluate the subjective and physiological responses, controlled luminous conditions in VR were used to replicate an office room that was lit by both natural and artificial lighting. Virtual environments were considered appropriate for these studies as opposed to relying on daylight from real windows, since in the latter photometric parameters would continuously change over time [20-22]. Other extraneous variables (e.g., temperature, humidity, and noise) could also be controlled in the test room. Across different experimental conditions, the illumination levels can also be maintained in VR settings, which can affect the investigated visual stimuli perception if left uncontrolled [15]. Using the validated VR approach described in section 3.3.1 and detailed in appendix A1, the physical and photometric conditions of the test room were presented within VR environments. The processes of generating the immersive environments for view perception studies are detailed in appendices A2 and A3.

In the first experiment, differences in view perception due to different observing locations was selected as a case study; as the dynamic criterion of observer and views is not well understood in literature (section 2.5). Three different distances from the window were tested: Close, Middle, and Far. The middle location was placed at the median value of the distance between the window and the rear wall of the room, and the Close and Far locations were selected based on the minimum standards for office furniture alignment [121], which allow for a 0.80 m space at both ends of the room. The same locations were replicated in the virtual environments. In the second experiment, view perception from different window sizes was investigated for two reasons: to explore the inconsistent results in the literature due to methodological limitations (section 2.2.2.1); and to reflect one of the window design factors affecting view perception besides other window performance-related systems (daylighting and energy). Combining the latter with daylighting and energy analysis could provide an all-inclusive approach to assess window performance. Five different window sizes (WWR) were tested in this experiment including 30%, 20% Wide, 20% Narrow, 10% Wide, and 10% Narrow.

The test room described in section 3.2 was used in the view perception studies. The office was located on the first floor and the view from the window is considered a neutral with a mixed of urban and natural elements (Figure 3-3) which would be considered by the green building practice guide BREEAM to be an adequate view [67].

The room had a double-glazed window with 30% window to wall ratio that was masked with a matt white paper with similar reflective properties of the walls $\rho_{paper} \approx 0.7$ to create the smaller window sizes used in both experiments.

Figure 3-3. Window view as seen 0.8 m from the window

View quality perceived from 20% WWR from three different locations was used as this size is recommended in BREEAM for rooms ≤ 8 m in depth [67]. In the second experiment, view quality perceived through the five different window sizes was evaluated. In addition to the original 30% WWR, window size was reduced to 20% and 10% WWRs with different aspect ratios to explore the impact of window proportion on view perception. The wide 20% and 10% windows were created by reducing the original size of the window from all sides whilst the narrow 20% and 10% were obtained by reducing the original window from the upper and lower edges. In all conditions, view was always kept in the centre of the observer field of view.

The different window areas were masked with the matt white paper to reduce the window size and the resultant luminous environments were replicated in VR (i.e., the window size was amended before taking the images for each condition). The 360° images were captured from different locations in first case study, and after changing the window size in the second case study (i.e., the images were manipulated to create the different conditions so that the captured luminous environment faithfully reflects the actual luminous conditions). Both the observer location and window sizes affected the view perception as some parts of the view will be omitted due to the parallax effect in the first case study (discussed in section 2.2.3) and due to reducing window size in the second case study. The final view levels, tasks location, and participants locations are indicated in Figures 3-4 and 3-5.

Figure 3-4. Image (a): the test room dimensions. Image (b): (1) the three observing locations; (2) the three windowless baseline environments; (3) the three environments with view indicating the view size in the visual field; (4) the corresponding view content for each location

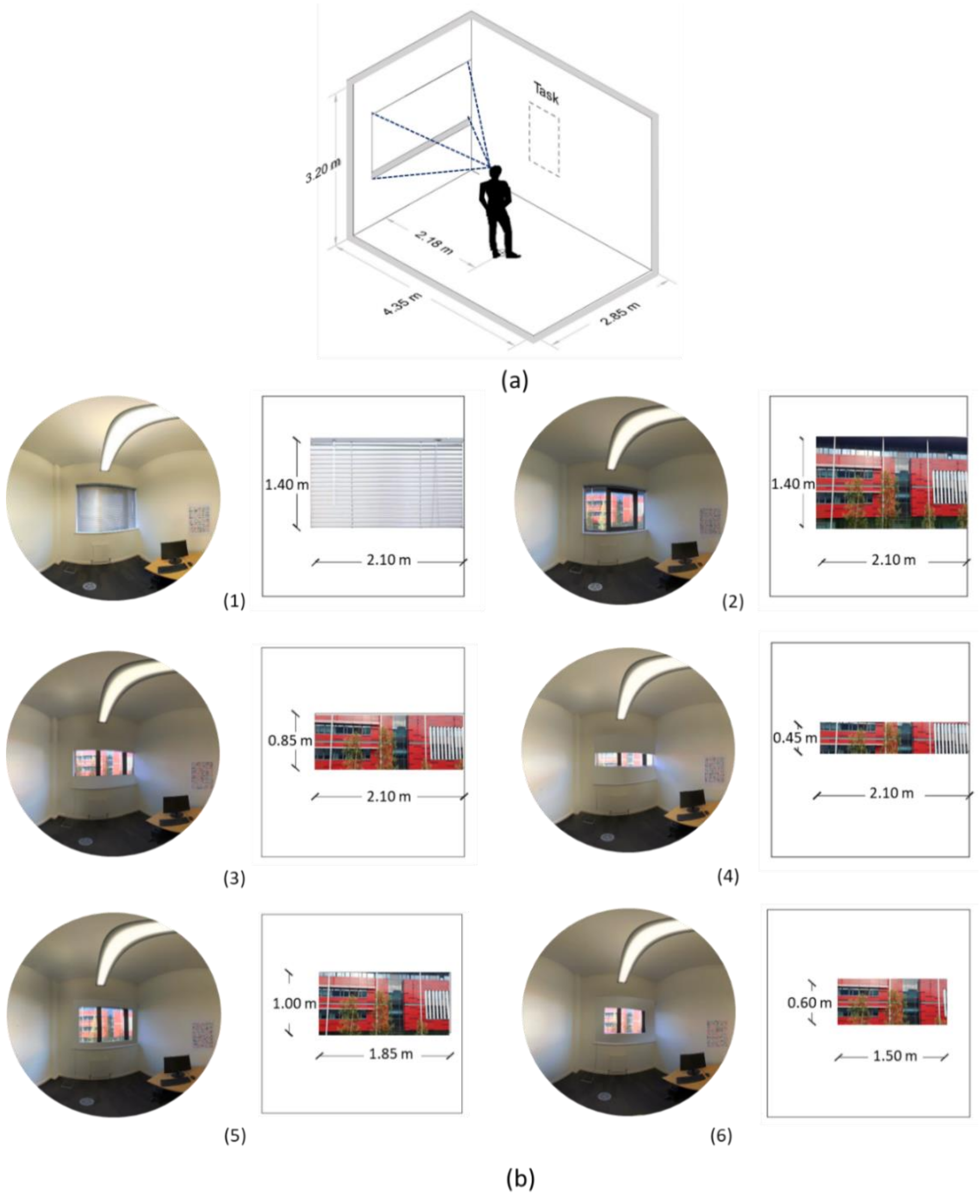


Figure 3-5. (a) The test room dimensions and observer location; (b) the window environment and the corresponding views for 1) the windowless baseline environment; 2) the 30% WWR; 3) the 20%N WWR; 4) the 10%N WWR; 5) the 20%W WWR; 6) the 10%W WWR.

In both experiments, the room contained furniture to resemble an office environment and the Stroop task (i.e., stress induction task used to increase stress levels of the participants) was mounted on a wall 1.50 m from the viewer position.

Overviews of both experiments indicating the different stages conducted are presented in the following sections.

3.3.2.1 Paper 2: Evaluating the Impact of Viewing Location on View Perception Using a Virtual Environment

In this experiment, the view quantifying method was developed and used to assess view perception using the validated physically-based 360º virtual environment in paper 1, as a representation method. View perception from three different viewing locations: Close, Middle, and Far was considered as the first case study on view perception. The three conditions were presented to thirty-two participants (N=32). Participants were from different ethnic backgrounds and voluntarily participated in the experiment and were either taught/research students or academic staff members at University of Nottingham recruited via posters and online advertisements. The participants comprised twenty-three males and nine females and the mean average age of the group was 28 years (SD= 6.08). This sample is different than the one used in the other experiments. None of the participants reported any colour vision problems, and 15 participants wore corrective glasses during the experiment. The experiment lasted for approximately 90 minutes and participants were given a seven-minute break between each test condition. The study was conducted during summer months (July-September) during the second year of the investigation.

The study utilised a comprehensive method by collecting subjective and physiological evaluations. A stress-recovery methodology to assess restorativeness effects was used by presenting a window view observing period after a stressful task was performed. Subjective assessments included questions on view restorative ability, view content and size preferences, view valance/arousal, and positive and negative effects. Physiological measures included skin conductance, heart rate, and heart rate variability. Results showed significant differences in subjective parameters and measures of skin conductance. Decreased view quality was reported as participants observed the view from the further viewing locations compared to the close position. The study highlights the importance of the informative content seen in the window view such as the sky and ground, which may impose limitations on recommended room depth and window design. The results of this study show that the design of window views has important implications on the health and wellbeing of building occupants.

The workflow of the different stages conducted during this experiment is illustrated in Figure 3-6 and detailed in Appendix A2. The paper includes the methodology used to evaluate view quality, its rational, the experiment design and procedure. In addition, the results are presented and discussed in the paper and conclusions are drawn. The results indicated that a subjectively preferred view is a restorative one which validates the proposed methodology to assess view quality by its restorativeness. Nevertheless, to add further validity to the proposed method, a second case study on view perception was conducted as described in the following section.

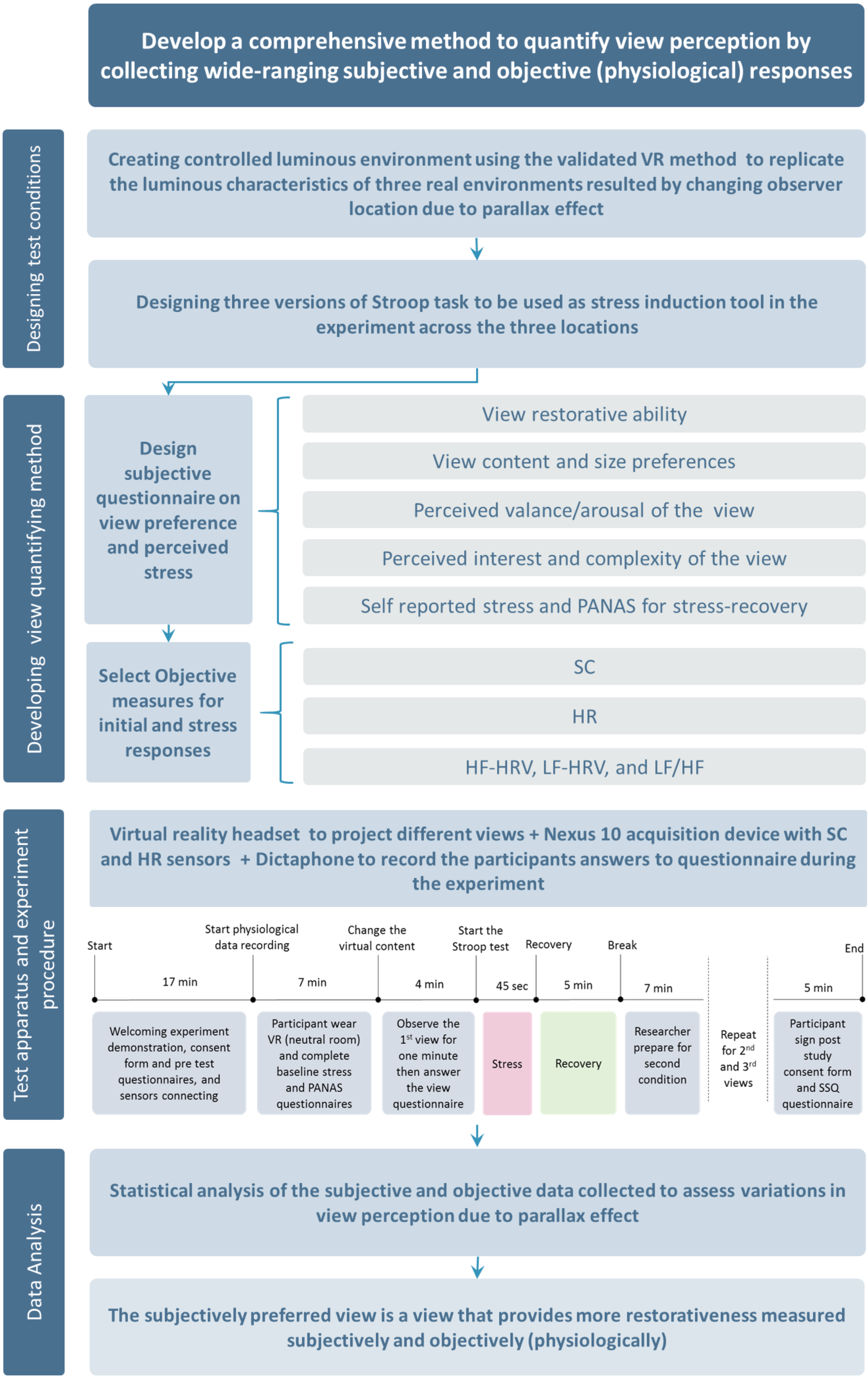


Figure 3-6. An overview of the experiment conducted in the second paper to develop a view quality quantifying method due to change in observer location

3.3.2.2 Paper 3: Optimising Window Size for View Perception, Energy, and Daylight

An efficient design of windows in built environments should consider its energy and daylight performance, and the connection to the outdoors provided by the views from the windows. The latter is insufficiently studied despite being a critical factor contributing to occupants' wellbeing and satisfaction with the indoor environment. While window size optimisation has been investigated for daylight and energy, its impact on view perception has not been comprehensively investigated. In this study, view perception was evaluated using the validated physically-based 360º virtual environment, in paper 1, with five different window sizes: 30%, wide 20%, narrow 20%, wide 10%, and narrow 10%, presented to twenty-five participants. The participants from different ethnic backgrounds voluntarily participated in the experiment: 14 males and 11 females with mean age of 27 years (SD= 5.26). This sample was different than the one used in the other experiments. None of the participants reported any colour vision problems, and 15 participants wore corrective glasses during the experiment. The study was conducted during winter (January-February) during the third year of the investigation.

The study employed a comprehensive evaluation method (similar to the one used in the previous experiment but with additional measures) that incorporated collecting subjective and physiological evaluations. Subjective assessments included questions on view restorative ability, view content and size preferences, view valance/arousal, stress, and positive and negative affects. Physiological measures included skin conductance, heart rate, and heart rate variability. Results showed significant differences in subjective parameters and measures of skin conductance and heart rate variability. Decreased view quality was reported as participants observed the view from smaller window sizes compared to the 30% case.

In addition to the view quality perception, the corresponding energy and daylight simulations were performed to provide a holistic assessment to assess window performance. This experiment was written in a journal format paper presented in Appendix A3 and the workflow of the different steps used to conduct the experiment are presented in Figure 3-7. The paper includes the methodology used to evaluate view quality, its rationale, the experiment design and procedure, and energy and daylight simulation assessment methods. In addition, the results are presented and discussed in the paper and conclusions are drawn. The results indicated that a subjectively preferred view is a restorative one which further confirmed the results from the previous paper (i.e., the validity of the proposed methodology to assess view quality by its restorativeness). Additionally, the study highlights the importance of considering the view quality when optimising window design as optimising window size for energy and daylight alone might not guarantee view restorativeness for building occupants, and ultimately affecting their health and wellbeing.

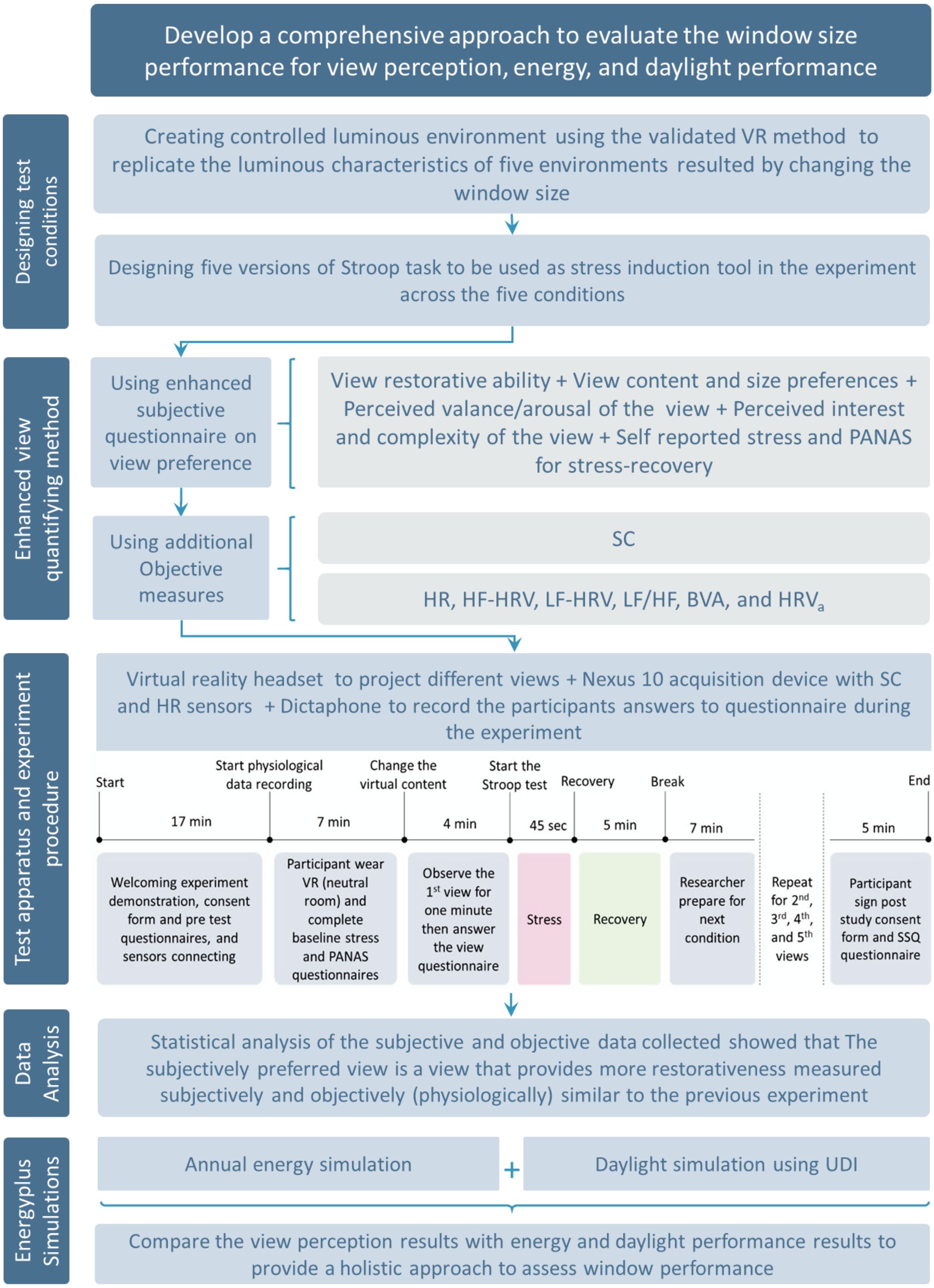


Figure 3-7. An overview of the experiment conducted in the third paper to develop a comprehensive method to assess window performance for view perception, daylight, and energy performance

The data collected in papers 2 and 3 was analysed in a final step to further validate and refine the proposed method to quantify view quality, as described in the following section.

3.3.3 Paper 4: A Refined Methodology to Quantify View Perception

Indoor environmental quality has a major impact on occupants' perceptions of their immediate environment. Views from windows are key factors that affect the indoor environmental quality perception by providing connectivity to the outdoor environment and restorativeness from stress which affect occupants' comfort, productivity, health, and wellbeing. Nevertheless, views from windows are usually overlooked when building envelope performance is evaluated. The absence of a robust methodology to assess view perception (i.e., to quantify view quality) and the difficulty to conduct experiments in continuously changing daylit environments might be the reasons for not considering the "view" factor in similar research.

This study provides guidance to assess view perception based on reliability tests and correlation analyses of subjective and objective data collected during the two experiments on view perception. The study was written in a journal paper format for publication as indicated in (Appendix A4) and provides guidance by offering a refined method to assess view perception in future studies for more occupant-oriented evaluations of building envelope and window design. The statistical tests used for the reliability test on the proposed questionnaire on view perception and the correlation tests performed are detailed in the paper.

An overview of the study summarising the different steps conducted and the workflow are indicated in Figure 3-8 and detailed in appendix A4.

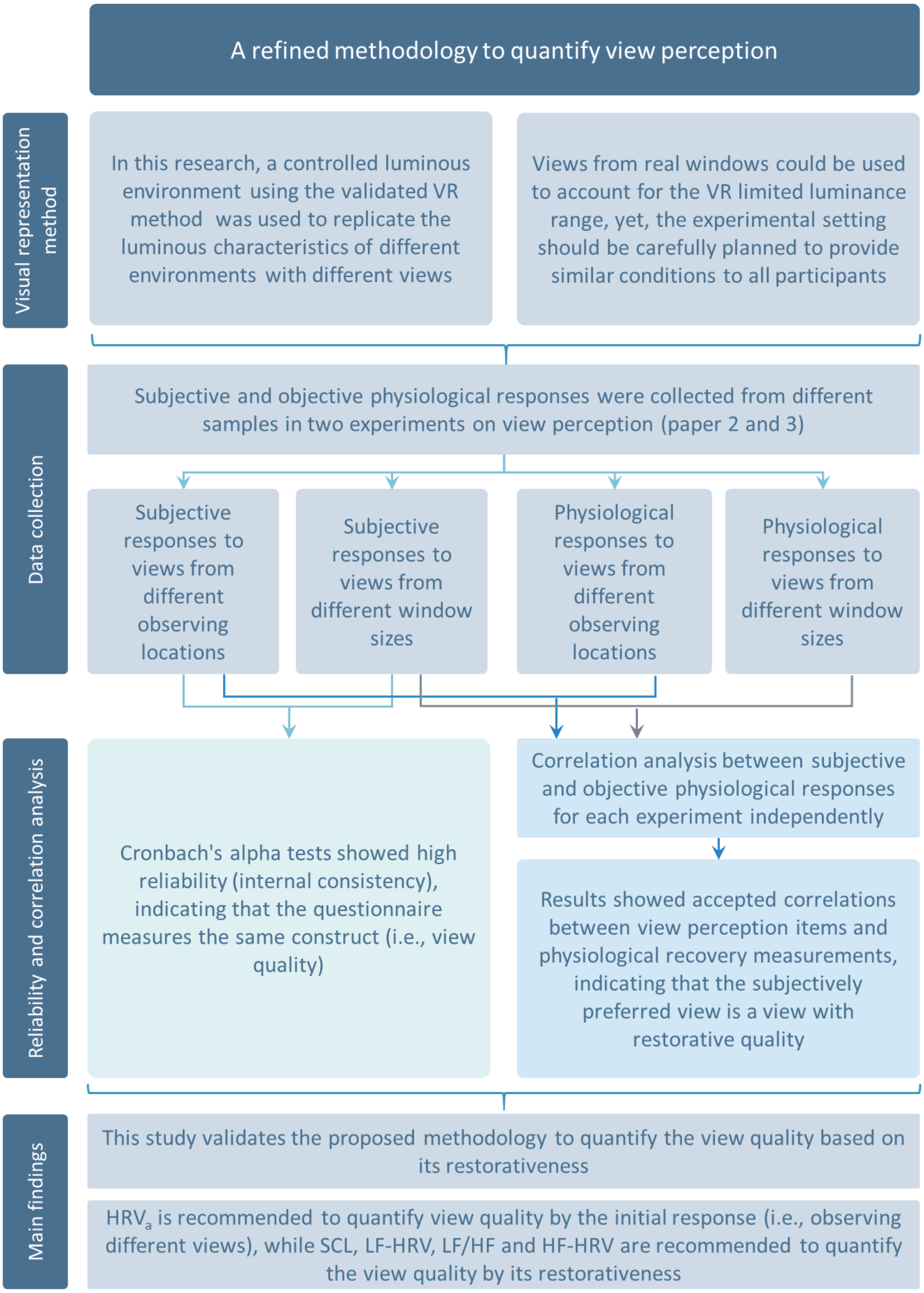


Figure 3-8. An overview of the steps conducted in the fourth paper to provide a refined method to quantify view perception

The main conclusions from each experiment and their limitations are presented in the following chapter.

Chapter 4

Conclusions and Future Work

4.1 Conclusions

Window design and views provided from windows are key design parameters in the working environments that affect occupants' health and well-being. Views provide a connection to the outdoor environment and offer an escape from stressful monotonous working environments by providing recovery and restoration. The studies conducted on view perception focussed on view content in terms of naturalness preference in comparison to built urban views. In contrast, other window-view-related parameters were less understood, especially, view quantity. View quantity can be affected by observer-related factors (observer relative location to the window) and window design-related factors (window to wall ratio, aspect ratio, shading devices, and smart window applications); hence, affecting the visual connection provided to the outdoors. Existing studies were either limited to subjective assessments on view preference or limited by the representation methods used in their investigations.

In this research, an alternative representation method that replicates a real luminous environment was developed and validated, and a comprehensive method using subjective and physiological responses was developed to quantify view quality in order to establish an all-inclusive method to assess view perception. The developed method was used to assess the impact of view quantity provided in view perception and was evaluated against other window optimization parameters (lighting and energy performance) in order to attain a holistic and comprehensive approach to assess window performance. The following sections conclude the findings of this investigation, present limitations, and suggest future research.

4.1.1 Conclusions from Paper 1: Developing an Innovative Method for Visual Perception Evaluation in a Physical-Based Virtual Environment Experiment

A novel method for evaluating the use of a virtual environment as a replacement for a real luminous environment was introduced in this chapter. The method was based on a physically-based 360^{o} imaging technique and was validated by objective task performance and subjective responses to the perception of scene visual quality, lighting, and personal impressions of the virtual environment.

The conclusions from this experiment are: 1) visual task performance in a virtual environment requires a relatively longer time than a similar task completed in real environment; 2) the subjective assessments showed no significant difference for the perception of the lighting appearance (i.e., brightness, colour temperature, and distribution) and high-order perceptions (i.e., pleasantness, interest, spaciousness, excitement, and complexity) of the room between the two environments; 3) the results of contrast and colour naming tasks indicated that both contrast and colour replications were acceptable; yet, significant difference was found in subjective assessment of visual quality attributes (i.e., detail, contrast, and colour vividness) as they might be affected by the limited resolution of the current virtual reality headset; 4) the use of VR causes minor short-lived reported physical symptoms, and produces similar stress and positive and negative affect levels after task performance compared to those reported in real environment.

In general, the developed method in this experiment is a promising alternative method to investigate real luminous environments, produce similar luminous properties, high-order perceptions, and stress from task performance, and guarantee the reproducibility of the experiment setting.

4.1.2 Conclusions from Paper 2: Evaluating the Impact of Viewing Location on View Perception Using a Virtual Environment Experiment

The impact of viewing position on view perception occurred due to the visual parallax effect was comprehensively investigated in this experiment. Visual parallax resulted from occupants observing a window from different relative positions in a physically-based 360^{o} virtual environment at three different viewing locations: close, middle, and far. The study employed a comprehensive method by collecting subjective assessments on view restorative ability, view content, size preferences, view valance/arousal, and positive and negative affects, and physiological responses using skin conductance, heart rate, and heart rate variability; considering stress-recovery methodology to assess view quality by its restorativeness. The designed methodology identified statistically significant differences in view perception in the evaluated measures used.

The conclusions from this experiment are: 1) view quality is significantly influenced by the viewing location of the participant from the window, measured by subjective and physiological responses (i.e., increased view quality was reported the closer the participant was located from the window within the virtual environment; 2) at a certain distance from the window, view quality between different viewing locations is perceived with no difference as detected by subjective and physiological responses, and the sky being no longer visible at this distance was proposed as the cause; 3) the increased view quality, reported by participants when located closer to the window, was supported by recovery physiological measures, indicating that a subjectively preferred view is a view that provides restorativeness; 4) recommended window to wall ratios given by standards might not guarantee the view benefits (restorativeness) across the room; instead, the window's 'position and dimensions in relation to the view content should be considered.

4.1.3 Conclusions from Paper 3: A Holistic Approach to Assess Window Performance: Optimizing Window Size for View Perception, Energy, and Daylight experiment

An all-inclusive method to assess window performance for view perception, energy and daylight was presented in this study. Five different window sizes with corresponding views were presented for participants using a 360^{o} physically-based virtual environment. Subjective and physiological measures were used to quantify the differences in view perception based on restorativeness from stress and view preference. The results were assessed in relation to energy consumption and daylight performance simulated for different window sizes. The designed methodology identified significant differences in window performance for view perception, daylight, and energy for different window to wall ratios.

The conclusions from this experiment are: 1) window size and layout have a significant influence on view quality measured by subjective and physiological parameters, whereby decreased view quality was reported as window size reduced with exaggerated proportions, as seen in the virtual environment; 2) subjective and objective responses showed that at a certain decrease in window aspect ratio, view quality (restorativeness) becomes significantly lower, suggesting that exaggerated proportion has a major impact on view quality; 3) for certain climates, the optimized window size for energy consumption, daylight performance, and view perception are different; hence, optimizing one aspect of window performance could compromise occupants’ health and well-being; 4) participants rated 30% WWR when built view content is provided in this experiment with similar mean ratings to the 20% WWR used in the previous experiment which incorporated sky, indicating that room and window design concerning occupant location might offer more agreement among optimized window to wall ratio for view perception, energy, and daylighting.

4.1.4 Conclusions from Paper 4: Refined Methodology to Quantify View Perception

To attain the main aim of this research, further statistical analysis was conducted on collected subjective and physiological data from view perception experiments, to further validate the physiological evaluations as objective measures to quantify the view, to provide a guide on what are the best physiological signals to use for different parts of the research and to evaluate the strength of association between subjective and objective responses on view perception to provide a refined methodology for future research on view perception.

The conclusions from this analysis are: 1) the various selected questions on view parameters proposed to subjectively quantify view perception showed high internal consistency and measured the same construct (i.e., view quality); 2) for data collected in both experiments, the correlation analysis showed acceptable correlations between view perception items and physiological recovery measurements, implying that a subjectively preferred view is a view with restorative quality and validating the designed methodology to quantify the view based on its restorativeness; 3) heart rate variability amplitude is recommended to quantify view quality by the initial response (i.e., discrete stimuli of different views), while tonic skin conductance level and heart rate variability measures are recommended to quantify the view quality by its restorativeness; 4) Physiological data interpolation should account for the experiment design and corresponding subjective responses as positive and negative correlations during the different experiment events (i.e., initial response and during recovery) were found; 5) Both subjective assessments of the view and physiological data are needed for view quality assessment.

4.2 Research Limitation

This investigation on view perception has been achieved using a systematic approach to develop and validate a physically-based virtual environment to be used as a representation method, develop a subjective-objective comprehensive evaluation method to quantify view perception using different observer location, apply the valuation method to assess different window sizes impact on view perception and corresponding energy and daylight performance for holistic window performance, and validate the designed view quality evaluation method for future studies. In contextualising the findings drawn, the following limitations should be considered:

1. The developed virtual reality method in Paper 1 was validated for a wide range of luminous, high order perception, and post-task stress parameters; thus, the application of this methodology should be limited to the validated parameters. This method was adopted in order to isolate the effect of experimental interest (i.e., control changes in the experimental setup that might affect the collected data [122]). Although the overall appearance of the scene can still be correctly perceived, some visual attributes cannot be investigated with this method. I.e., due to low luminance values and the low resolution offered by the currently available virtual reality headset, glare and visual tasks speed and acuity cannot be evaluated.

2. Due to the virtual reality resolution limitation, the role of the Stroop task used in view studies in papers 2 and 3 limited to stress levels elevating for participants; hence, view quality impact on cognitive performance was not included.

3. In both experiments on view perception, content from the window was limited to an urban view and was only assessed in a relatively small cellular office environment. Further view contents, room functions, with different room sizes and layouts could provide more insight into view quality perception.

4. The research showed that people prefer to sit close to windows, this preference needs to be assessed considering other environmental related factors (e.g., thermal, acoustic, glare, etc.,) and view related factors (i.e., safety, privacy, distraction, the proximity of exterior view elements), which could affect occupants' preference, performance, and well-being.

5. In view perception study from different window sizes, a limited range of window to wall ratio (between 10% and 30%) was investigated due to the limitation of the office used in this experiment.

6. The unwanted simulator sickness symptoms that were reported by the participants following the use of virtual reality technology is another limitation. Although these symptoms are often linked to the application of VR environments [48], they are usually minor and short-lived [123]; yet, this should be considered when similar experiments are designed.

7. Window optimizations for view perception, energy, and daylight presented in this work were limited to a south-oriented window and the three investigated climates. Daylighting performance optimization was limited to useful illumination level and using other metrics of visual comfort (e.g., uniformity) might reveal different

outcomes. Nevertheless, the methodology designed is replicable and could be reproduced with different climates and orientations.

4.3 Future work

4.3.1 Virtual Reality for Visual Perception

1. The results obtained in this work for the adequacy of VR technology in visual perception along with the mobility of the used device showed VR as a promising tool that can address the challenges presented by continuously changing conditions in a real daylit environment. Hence, the enhancements of the VR lens (to enable HDRI display) are encouraged to benefit more attributes of lighting to be studied (e.g., glare).
2. Further studies on more levels of the investigated parameters (i.e., brightness, colour temperature, etc.) are encouraged to increase lighting parameters that could be investigated with VR technology.

4.3.2 Future Studies on View Quality Assessment

1. The results concluded in this investigation were based on experiments conducted in a controlled lighting environment. Studies under daylight conditions when other visual comfort variables are introduced (i.e., glare) should be conducted in future.
2. Views with different urban contents with multiple levels of built, nature, climate, and moving elements, in addition to the interaction between view perception and other environmental parameters including thermal comfort, acoustic, and ventilation are encouraged for future studies.
3. View perception impact on cognitive task performance and sustained attention should be considered as an additional objective measure of view quality.

4.3.3 Future Studies on Window Design and View Quality Assessment

1. The impact of window design features such as window shape, location, shading, and smart windows applications on view quality perception and connection to the outdoor is encouraged. In addition, the corresponding lighting and energy performance could be assessed to provide a complete understanding of a window's performance.

2. Investigation of the impact of number and window placement on view perception from different locations in the room is encouraged to assess restorativeness in deep parts of the room.

3. Additional studies with a wider range of window sizes to evaluate the impact of window enlargement on subjective preference as other psychological aspects, including privacy and control, are encouraged.

4. As for the same window size, placing occupants closer to the window will increase the restorativeness of the view (if the sky component becomes visible) more than increasing the size of the window to 30% from the same observer location. The impacts of window size and observer location were investigated separately, and the interaction between different factors (observer location, size, and content) should be considered in future research to give further insight on view perception, and to provide more window design alternatives to optimize energy and daylight performance.

4.4 Concluding Remarks

The systematic investigation in this research has explored the adequacy of using virtual reality in visual perception studies. It has also investigated the impact of view quantity provided by different viewer locations (view size in observer visual field) and different window sizes; the latter was assessed against energy and daylight performance to provide an all-inclusive approach on window performance. The main findings that can be drawn from this study are:

- No significant differences in the investigated lighting perception and impressions of the room perceptions were detected between the real environment and its replicated physically-based virtual environment, as reported by test subjects.
- View quantity provided by different viewer location due to parallax effect and by different window sizes showed significant differences between different conditions subjectively and objectively.
- Window to wall ratio given in standards might not guarantee similar psychological and physiological benefits of window-view across the room, especially, in deep parts of the rooms.
- In addition to energy and daylight performance, view perception should be included in window design optimization studies.
- The detected correlations between subjective and physiological responses were relative to those values accepted in the literature (between small and moderate thresholds). Further studies are needed to verify these correlations and replace the questionnaires with exclusively objective physiological data. Meanwhile, both subjective assessments of the view and physiological data are needed for view quality assessment.
- The proposed comprehensive method using subjective and physiological assessments tools was able to quantify view quality and validated the notion that a preferred view is a restorative one. This method could be used to weigh

up the impact of different factors on view quality to ultimately provide a complete understanding of view perception.

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Appendix A1

Paper 1: Developing an Innovative Method for Visual Perception Evaluation in a Physical-Based Virtual Environment

Developing an Innovative Method for Visual Perception Evaluation in a Physical-Based Virtual Environment

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Abstract

With the developments in virtual reality technologies, significant researches have been conducted for human response on indoor luminous environment using head-mounted display to replace those in a real environment. However, the limited resolution and luminance values offered by the devices might affect the perceived appearance and high-order impressions in the simulated virtual environment. In this study, a simulated 3-dimensional virtual office was compared against a real one. Both settings presented similar physical and luminous conditions to twenty participants (N=20). The study investigated subjective and objective visual responses and participants' interaction with the virtual environment based on measurements of perceived presence. Subjective assessments included questions on luminous environment appearance (brightness, colour-temperature, distribution) and high-order perceptions (pleasantness, interest, spaciousness, excitement, and complexity). Objective assessments measured contrast-sensitivity and colour-discrimination tasks to assess visual performance across the two representation environments. Results showed no significant differences between the two environments based on the studied parameters, indicating a high level of perceptual accuracy of appearance and high-order perceptions. Minor physical symptoms related to the headset use and high level of perceived presence were found, indicating the proposed methodology's capability to provide realistic immersive environments. Although attributes regarding scene quality (colours, details, and contrast) were perceived significantly different to the real environment, objective tasks showed that similar contrast and colour appearance can be produced in the virtual environment with minor impact on fine-details due to limited resolution. Virtual reality may be a promising alternative representation medium to investigate visual perceptions as the overall appearance of the scene can still be correctly acquired.

Keywords: Visual performance; Virtual reality (VR); Visual quality; Virtual luminous environment; Lighting; Lighting perception.

A1.1 Introduction

A continual research has led to the development of simulated virtual environments that could be comparable to the experiences felt in real physical environments. This can be achieved by the use of photographs [1-3], 2- or 3-dimensional rendered images displayed on screen [3-5], or reduced scale mock-ups [6-10]. Recently, studies have been using immersive Virtual Reality (VR) as an alternative media to present the visual setting in indoor lighting studies [11-14]

VR technology can display the visual stimuli in a more comparable field of view (i.e., subjects are immersed in the scene and the visual stimuli can be presented to the same scale of the original environment); an essential parameter when evaluating virtual and real environments [1]. Also, it provides subjects with stereoscopy vision (3-dimensional) which provides the depth perception that cannot be obtained when mesoscopic 2-dimensional scenes are assessed [15]. Moreover, it allows the interaction between subjects and the presented scene which can greatly improve the realism for user-experience studies, in which the interaction and immersion are important factors [4, 13, 16, 17].

The mobility of VR technology provides the flexibility of apparatus allocation allowing the reproducibility of consistent conductions of the experiments [13]. Also, the immersivness provided by the VR minimises the artificial nature of the experimental setting as subjects cannot see the setup or the experimenter, which leads to the control of personal factors that can affect the results as people tend to change their behaviour in the presence of others [18].

VR also allows for more control over different environmental factors [11] for example, the variation in daylight conditions caused by changing sky conditions, which is one of the main challenges in experimental studies using windows [13, 19]. Hence, VR can maintain the levels of illumination observed within the windows and the surrounding environment, which can affect the visual perception and the assessment of investigated stimuli [19]. Additionally, the rapid change of visual stimuli in VR environments reduces the time needed to perform the experiment. This overcomes the limited settings that are usually available for researchers when real environments are used. Also, the experimenter can replicate the same experimental setup with a wide range of visual stimuli and the same surrounding environmental factors.

The literature suggests that the VR immersive environment could be used as a representative method to study luminous environments in terms of scale, immersiveness, and controlled luminous conditions. These factors should first be assessed to validate the use of this technology when they are compared against real visual environment, however, few studies have been conducted in this area. In a study by Chamilothori *et al.* [13], stereoscopic physically-based renderings were evaluated in terms of four lighting impressions (i.e., pleasantness, interest, excitement, and complexity); along with satisfaction with the amount of window view, and found no significant difference on these parameters when compared to the real scenes. Presence, appearance attributes, and perceptual impressions of lighting using an immersive 360^{o}-video displayed smartphone VR were compared to real environments in a recent study [14]. Three reference scenes with average illuminance 800 lux on the work plane (75 cm above the floor) and three correlated colour temperature (CCT) were used: warm white (3000 K), neutral white (4000 K) and cool white (5500 K). Two lighting attributes (open/close and diffuse/glaring), presence, and overall satisfaction were perceived with no significant difference. However, in this study, it is important to highlight that the VR scene was not calibrated with photometric measurements of the real one. In another study [11], The difference in performance between bright and dark real office was assessed against the difference in bright and dark simulated rendered 3-dimensional environments. The study results showed no statistically significant differences between the two comparisons. However, the comparisons that were performed did not consider a direct evaluation of the same conditions (e.g., bright real versus bright virtual) between real and virtual conditions, nor did the authors state the exact luminous conditions in both environments (i.e. luminances or illuminances), which highly affects task performance [20-22]. The same limitations were found in a study on lighting preferences for task performance [12]. Validation studies are limited and mainly focus on one specific aspect of the luminous environment. A replication of the results is required to further confirm the applicability of VR when used to evaluate the luminous conditions of any visual environment. Also, the studies were either limited to subjective evaluation or lack the physical calibration of the VR content. Visual quality attributes (i.e. colour, contrast, or detail) are yet to be validated.

The main aim of this study is to evaluate the differences in visual perception (subjectively and objectively) under real and virtual reality conditions by comparing a simulated 3-dimensional virtual office developed using physically-based image technique against the real office. Several criteria were used to assess the luminous environment in a more comprehensive approach (i.e., appearance, high-order perceptions, and visual quality). This evaluation was accomplished by: (1) creating controlled luminous conditions in a typical office room under artificial lighting conditions; (2) developing a replica of the office room (in (1)) based on its physical and luminous conditions in a 3-dimensional virtual simulated setting using physically-based images; (3) evaluating the same subjective and objective visual responses under real (1) and virtual (2) conditions; and (4) evaluating other parameters related to the use of immersive virtual reality environments.

A1.2 Experimental Method

A1.2.1 Experimental Setup

To assess the research objectives, a test room with a controlled luminous environment was prepared. The physical and photometric conditions of this test room were replicated and presented within a virtual reality environment. An experiment under controlled artificial lighting conditions was considered appropriate for this study; as opposed to relying on daylight from real windows, whereby several uncontrollable parameters (i.e., spectral properties of the source, light intensity, etc.) would continuously change over time [21, 23, 24]. Also, other extraneous variables (e.g., noise, temperature, and humidity) could be carefully controlled.

A1.2.2 Test room

An office-like test-room located in Energy Technology Building (University of Nottingham, UK) was used. The room had internal dimensions of 4.35 m x 2.85 m and a floor to ceiling height of 3.2 m (Figure A1-1). The internal walls of the room had reflectance (ρ) properties: $\rho_{wall}\approx$ 0.7, $\rho_{floor}\approx$ 0.1, and $\rho_{ceiling}\approx$ 0.8. To mask daylight entering the room, the window was covered with opaque matte-white paper with similar reflectance properties to the walls $\rho_{paper}\approx$ 0.7. The reflectance properties were estimated using the Munsell values [25]. The room contained furniture to resemble an office working environment. Visual tasks were mounted onto one of the room's walls at a height of 1.2 m from the floor. A standard office desk chair was placed perpendicular to the centre of the task and acted as the viewing position.

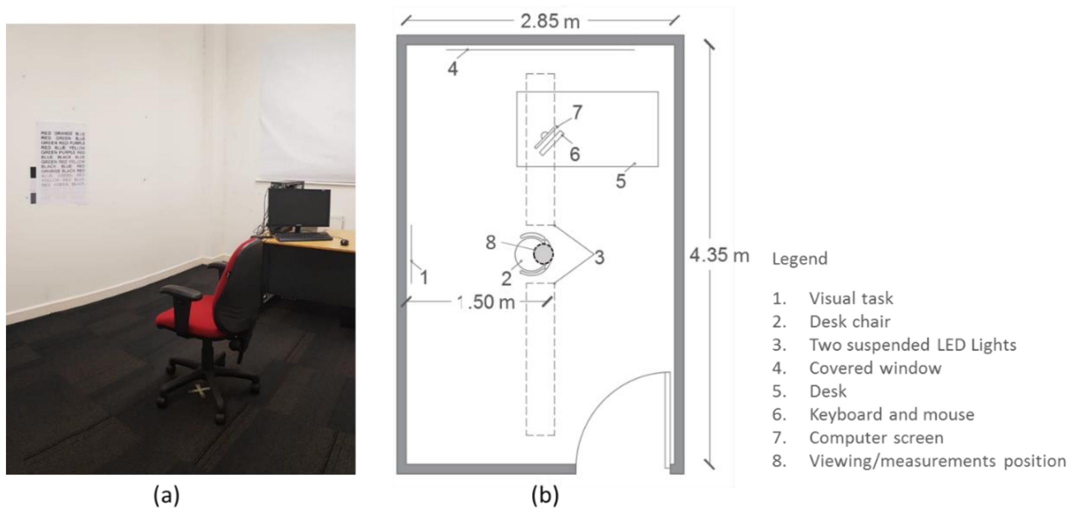


Figure A1-1. (a) Internal view of the experimental room, (b) layout of the experimental room

A1.2.3 Photometric Measurements

The following photometric equipment were used to measure the luminous environment of the test-room: 1) Canon EOS 5D camera equipped with a fish-eye lens (Sigma 4.5 mm f/3.5 EX DG) mounted on a tripod; 2) Hagner S3 photometer; 3) Minolta chroma-meter CL-200; and 4) Skye DataHog 2 illuminance data-logger. The camera was mounted on a tripod at 1.20 m from the floor corresponding to subjects seated eye level [26] and 1.5 m from the task wall.

Using conventional photographic methods, the camera image pixels can be used to obtain luminance measurements of any visual environment [27]. Such cameras have the ability to capture a large range of luminance values that will be stored within the image pixels correlated with measurements of different points in the captured scene [28]. To measure the luminous environment of the test room, a high dynamic range image (HDRI) was obtained from seven low dynamic range images (LDRI) with different exposure values by varying the camera shutter speed. The used camera settings are indicated in Table A1-1 along with the exposure values (EV) which were calculated using aperture size (f) and exposure time or shutter speed (v) based on Equation (3.1) [29].

$$EV = 3.32\, log10 \left(\frac{f2}{v}\right) \qquad \text{Equation (3.1)}$$

Table A1-1. Charge coupled device (CCD) camera settings for each of the seven LDRI

Image	White balance (K)	Sensitivity (ISO)	Exposure time (1/s)	Aperture (f/n)	Exposure Value (EV)
1			1/400		12.98
2			1/125		11.30
3			1/40		9.66
4	4500	100	1/13	4.5	8.04
5			1/4		6.34
6			0.8		4.66
7			2.5		3.02

The lowest sensitivity (ISO) 100 was used to reduce the noise in the HDRI with fixed and correct white balance (i.e., correct colour temperature) to maintain consistent colour space transitions [27]. For the camera white balance, 4500 K was used as the light colour temperature which was measured using the chroma-meter CL-200 (accuracy ± 0.02 %). The seven LDRI were combined into an HDRI using Photosphere software [30]. Photosphere generates a camera response curve based on the LDRI series that shows the relationship between the pixel and its related luminance value, which can be calibrated using a single point luminance measurement within the visual scene. This luminance value was taken by calibrated Hagner S3 photometer (accuracy ± 0.03 %) and was used to calibrate the HDRI.

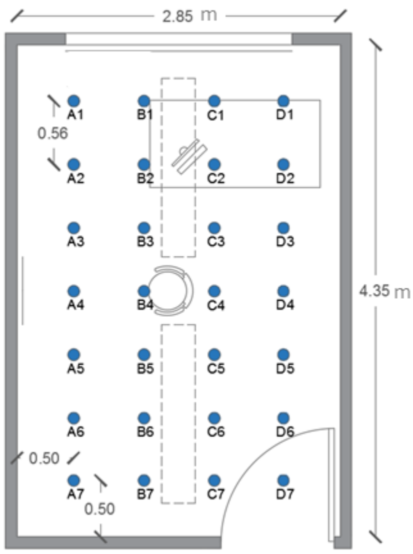
Since participants will evaluate the luminous conditions of the entire room, the HDRI was captured six times at different viewing directions to cover the visual scenery (Figure A1-6). The resultant six HDRI images were combined using PTguiPro software – a stitching software that supports HDR format [31] – and the resulting HDRI for the entire scene was calibrated with Photosphere.

An average of 50 independent luminance measurements were taken using a Hagner S3 photometer using (0.40 x 0.40 m) grid for divergent targets and (0.05 x 0.05 m) grid on the task area for the convergent targets from the camera position, and 13 points were selected to calculate the difference that represents coloured, greyscale, and low and high luminance targets to compare them to corresponding points in the resulting HDRI image of the entire scene, extracted using Photosphere software (Figure A1-2). This method was informed by Inanici [27]. The percentage error [32] in luminance for each point between spot-point luminance measurements and the resulting HDRI scene was calculated, and the resulting average error was 9.5 %, which is within the considered acceptable margin of average errors between 5 and 12 % [1, 27].

Figure A1-2. Panoramic image illustrating measurements points locations in the test room

The illuminance received at the camera lens and the illuminance received at the lux meter sensor were also compared to further validate the luminance captured by the images [26]. Using the software Evalglare [33], the illuminance received at the camera lens could be obtained. A chroma-meter CL-200 was mounted on a tripod at a height of 1.2 m to measure the vertical illuminance at the same position the camera was mounted facing the direction of the visual task. Measured vertical illuminance and calculated vertical illuminance were equal to 220 and 219 lux, respectively. This indicates the integrity of the used images. The minimum, maximum, and mean average luminances of the entire scene – as calculated from the HDRIs – were equal to 0.015, 23.9, and 7050 cd/m^2, respectively.

Twenty-eight individual measurements of horizontal illuminance on a regular grid at 0.8 m height from the floor level [26] were conducted, the average values were 498 lux (Figure A1-3). The light correlated colour temperature was 4500 K measured with the chroma-meter. The average illuminance is close to normal office lighting, which is considered to be ‘neutral’ in terms of both brightness [34] and perceived colour on the Kruithof chart [35].



Point	A	B	C	D
1	396	516	482	366
2	458	646	578	406
3	431	612	612	424
4	431	568	585	448
5	396	578	612	448
6	362	612	629	431
7	379	533	585	414

Figure A1-3. Horizontal illuminance grid points and their corresponding values measured in lux

A1.2.4 Visual Tasks

Two tasks were used in this study. The characters contrast test presented on an achromatic chart (with black and white chart characters) and Stroop test with a chromatic chart (with coloured chart characters) (Figure A1-4). Both tasks have been used in lighting studies [24, 36-38]. The tasks were mounted at 1.5 m distance from the observer position. The text size was 20 mm, creating a 0.76° angular size produced by character height, which is within the range needed for fluent reading (between 0.2 to 2°) [39].

Figure A1-4. Sample of contrast characters (left) and colour recognition tasks (right). For the character contrast test, the rows are denoted by five different contrast groups ranging from Black (first and second rows) to Grey 4 (ninth and tenth rows)

The tasks were used to measure subjects' performance using number of correct responses and completion time [40]. For the character contrast task, subjects were asked to read words to measure their cognitive performance, which have no significant meaning in the experiment (i.e., words representing colours) [22]. The words were randomly allocated to counterbalance any learning effect. Subjects were instructed to read the words, attempting to name even those they were uncertain of without any time constraints. The answers were recorded with a Dictaphone to measure accuracy, and the rate of time was measured using a stopwatch.

For the chromatic chart, Stroop test with four colours of words: Red, green, blue (RGB) and black was used. The colours represent the three main components of the RGB colour model [20, 21]. The same size and position of the previous task were used and the words were again randomly allocated. The four colours were measured using an Ocean Optics spectrometer USB2000+VIS-NIR-ES (Resolution: 0.1-10 nm varies by configuration) and Halogen Light source HL-2000 (0.25 % Stability of optical output), and had the following positions in the Chromaticity diagram: black (x= 0.306, y= 0.319), red (x= 0.490, y= 0.300), blue (x= 0.210, y= 0.190), and green (x= 0.301, y= 0.483), as shown in the chromaticity chart in Figure A1-5.

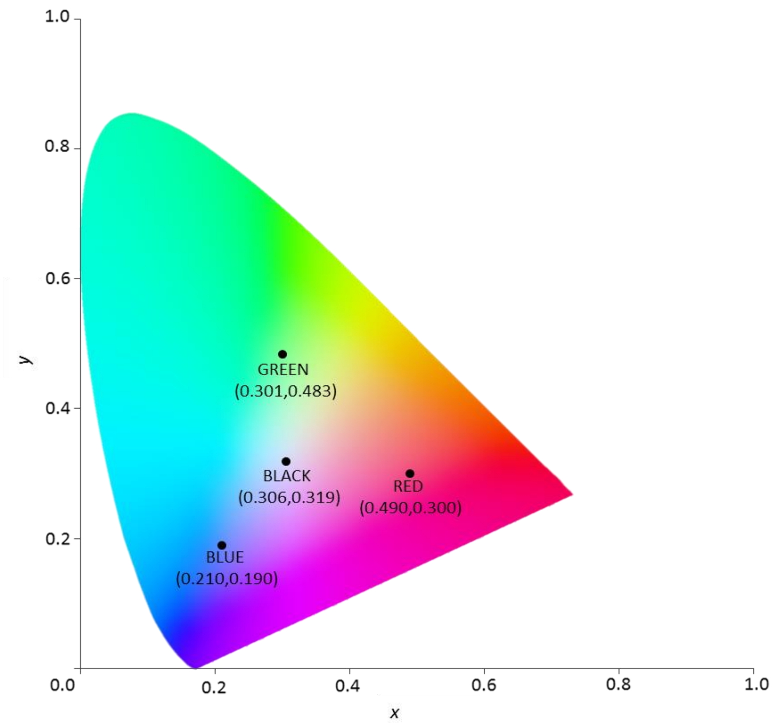


Figure A1-5. The position of the selected three colours on the chromaticity chart under a standard D65 light source

For this task, subjects were required to identify the colours of each word and their colour discrimination ability was measured by the words' colour correctly named divided by the total number of words' colours that could have been correctly named [40]. Subjects were instructed to name the colours of the words, attempting to name even the ones they were uncertain of, without any time constraints. For a second time, their answers were recorded with a Dictaphone to be analysed for accuracy, and rate of speed was measured using a stopwatch.

The achromatic chart uses a Stroop effect, which increases the difficulty of the colour naming task [41]. This may also influence stress levels; hence, self-reported levels were recorded using the stress and positive and negative affect schedule (PANAS) [42].

A1.2.5 Virtual Environment

In order to create a virtual environment that replicates the real conditions, physically-based images used on screens [1-3] and physically-based renderings [3, 11, 13] have been used in literature. Literature studies indicate that photographs are more accurate in representing the different luminous conditions than renderings particularly in an interactive panoramic view on screen method [3, 4]. Hence, physically-based imaging method was adopted in this study to replicate the real luminosity in 360^o 3-dimensional virtual environment.

A1.2.6 Physically-Based Images

To create the physically-based virtual luminous environment that replicates the conditions described in reality, four instruments were used: (1) Hagner S3 photometer to measure luminance; (2) DSLR camera equipped with a fish-eye lens and mounted on a tripod; (3) HTC-Vive (VR) headset; and (4) Minolta chroma-meter CL-200.

A total of six HDRI were created with each combined from seven LDRI with the same camera settings described in Table A1-1. The images were taken with a fish-eye lens covering 180^o in each direction. All images were taken from the same viewing position, aligning the entrance pupil axis to the rotation axis to minimise the differences between the various pictures composing the 360^o view [3] (Figure A1-6).

The resultant HDRI images cannot be directly viewed in the virtual reality head-mounted display due to the limited luminance ranges that can be displayed (~216 cd/m^2) [43], which is a common issue with available VR head-mounted displays [13]. To account for this, a tone-mapping process was used, which applies algorithms that compress large ranges of luminance values of the actual scene contained in the HDRI into a lower dynamic range. This allows images to be displayed within conventional devices, while reproducing visual impressions similar to those experienced in real environments [44-46]. Reinhard tone-mapping operator [47] was used for its ability to preserve details and naturalness of the processed images when compared to real scenes [3, 48]. The selected Reinhard tone-mapping was applied using Luminance-hdr software [49]. Certain parameters are left for the user to determine, such as gamma and key value, which influence the resultant tone-mapped image.

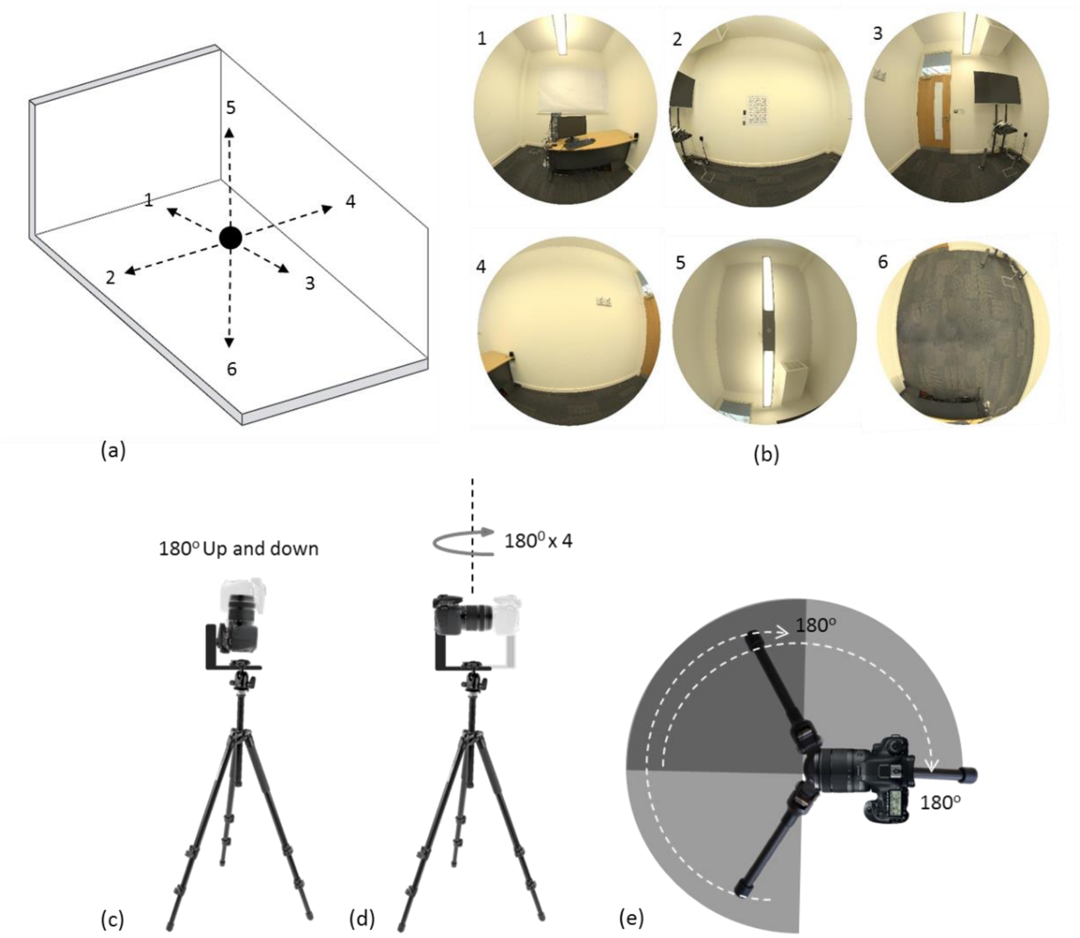


Figure A1-6. (a) Positions of camera with the six view directions, (b) resulting six fish-eye images, (c) Up and down camera position, (d) entrance pupil axis alignment with rotation axis, and (e) indication of covered view angle for each camera position

A gamma correction of 2.2 was determined for the VR screen using the screen response curve. According to literature, [3, 43], this curve can be obtained by displaying different RGB grey values ranging from (0, 0, 0) to (255, 255, 255) on the screen and measuring the resultant luminance values. For the VR headset used in this study, eight different shades of grey were used, and their corresponding luminance values were measured at the centre of the full field of the lens using Hagner S3 photometer in a completely dark room (Figure A1-7). It should be noted that 2.2 gamma value is usually used to simulate the human contrast sensitivity curve [44]. However, it is not always the same for all screens and it is more accurate to be measured. Also, the same value was found in human visual perception study for VR display that uses the same screen type (OLED) [13]. This curve can be used to calculate the difference between the real luminance values and those resultant from images displayed in the VR headset.

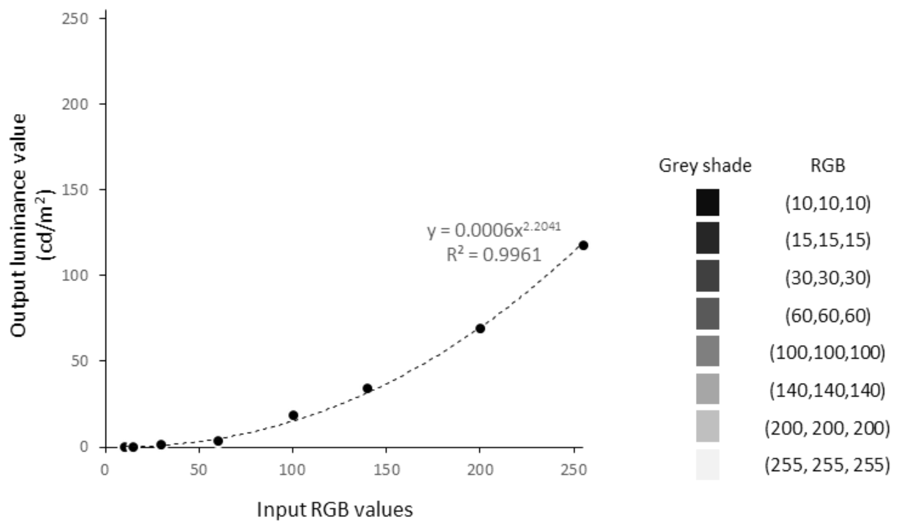


Figure A1-7. Gamma curve (luminance response curve for the used VR headset as measured at the middle of the lens) using Hagner S3 photometer

For the key value, a value of 0.01 was applied after a few adjustments were performed as it was found to create similar contrast ratios for both the grey and coloured tasks reported in section 3.2.4 based on Root-Mean-Square-Error (RMSE) [50] and Mean Absolute Deviation (MAD) [51]- between the real contrast and those resultant from tone-mapped image. This aimed to create similar luminous conditions in virtual and real environments. Using a key value that presents similar contrast was selected as it is considered the main factor in image perception preference according to literature [45].

To explore the impact of different key values on colourfulness of the resulting scenes, the colourfulness of these images was calculated using a MATLAB code detailed in [52], which quantifies the effect that image processing (i.e., tone-mapping) has on colour perception. The initial room design incorporated some colours besides the colourful task to allow test of the colour representation within the virtual environment, an important aspect of visual-quality representation [53]. The resulting values were compared with the colourfulness of the correct exposed panorama at the correct white balance which produces true colours. A key value of 0.01 was found to create the most accurate contrast and colourfulness (Figure A1-8) and was used in tone-mapping process. This method was applied for the six HDRI and without any colour adjustment to the resulting images to limit any bias in the image processing procedure.

	Key value=0.01	Key value=0.09	Key value=0.18	Key value=0.36
RMSE	0.119	0.267	0.251	0.214
MAD	0.104	0.241	0.241	0.199

Figure A1-8. RMSE and MAD between the real contrast and those resulting by tone-mapped images with different key values

The resultant six tone-mapped images were combined into a 360^{o} panorama using PTguiPro software with an additional image for the floor to mask the tripod area in the final image. In order to create the depth perception from two-dimensional images, the previous process was conducted twice (i.e., taking the six HDRI, tone-mapping process, and stitching into 360^{o} panorama) from two viewpoints 65 mm horizontally apart to reproduce the distance between the centres of observer's eyes [54] (Figure A1-7(a)).

The resulting stereoscopic image (the difference between the images for left and right eyes) will create the illusion of depth and the resultant image will be perceived as 3-dimensional [3, 13]. However, this method will create depth in two directions, and minimising the objects in the other two non-stereoscopic view directions will mask this effect. The two 360^{o} images for each eye were combined into a stereoscopic image using Stereo Panorama Converter software [55] and were projected in the VR head-mounted display using Whirligig software [56], which supports stereoscopic image viewing that will be perceived as 3-dimensional (Figure A1-9).

A HTC Vive head-mounted display [57] with computer of two 2.40 GHz possessors and NVIDIA GeForce GTX 1060 card were used along with Whirligig software, which supports the display of stereoscopic images, to display the immersive 360^{o} images. This will create an interactive viewing mode, whereby the viewed part of the scene will correspond to the subject's head position. The VR HTC Vive has a dual AMOLED 3.6'' diagonal screen with a resolution of 1080 x 1200 pixels per eye (2160 x 1200 pixels when combined) and provides 110^{o} nominal field of view.

The illuminance received at eye (10 mm from the lens) was measured using chroma-meter (CL-200) in a completely dark environment (i.e., absence of any other source of illumination). This was to verify that the illuminance from the VR display was similar to vertical illuminance measurement taken in the real luminous environment from the same viewing position: 194 compared to 220 lux when the scene is displayed. No changes were made to the projected images so that any evaluation of the luminous environment will be due to the used method.

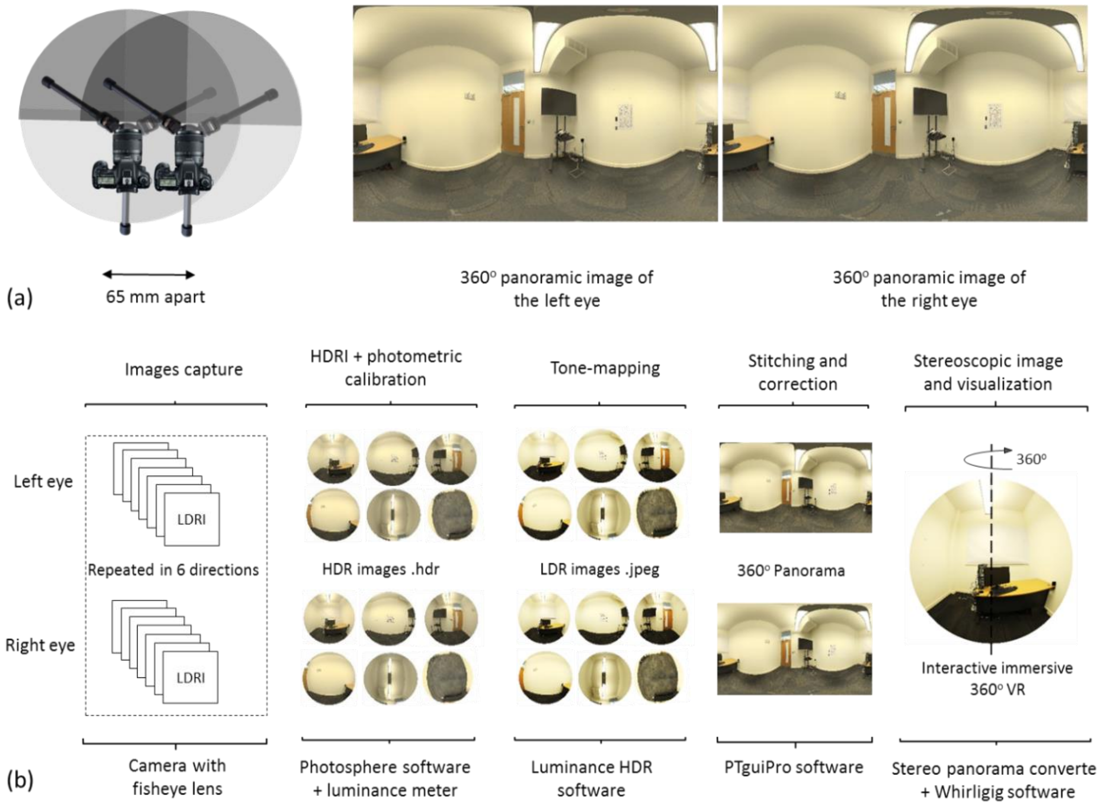


Figure A1-9. (a) Illustration of the stereoscopic principle to the left and the resulting stereoscopic image to the right, (b) Process for generation of the virtual environment

A1.2.7 Visual Tasks Properties in the Virtual Environments

Luminance values of the actual task were measured using Hagner S3 Photometer and the contrast ratios were obtained using Weber's formula (Equation (3.2)) [58] for both charts displayed in Figure A1-4, which were calculated using the background luminance of the task (L_b) and target luminance of the visual characters (L_t). Resultant values are presented in Table A1-3.

$$C = (L_t - L_b)/L_b \qquad \text{Equation (3.2)}$$

The visual properties were affected due to limitations of the current virtual head-mounted display as they cannot display HDR images. Hence, the tone-mapping process was applied as described earlier in the previous section using the key value that produced the contrast and colourfulness that resemble the appearance of the tasks in the real environments. Table A1-2 displays the real and virtual luminances and contrast values of the two visual tasks, and the percentage change in contrast across the two conditions.

Table A1-2. Luminances and contrast ratios of the different colours used in the tasks

Colour	Real environment luminance cd/m^2	Tone-mapped images relative luminance	Real environment contrast	Virtual environment contrast	Percentage change (%)
Black	9	0.06	-0.88	-0.89	1
Grey 1	11	0.11	-0.85	-0.79	7
Grey 2	26	0.27	-0.65	-0.47	28
Grey 3	48	0.42	-0.37	-0.18	50
Grey 4	65	0.49	-0.13	-0.04	69
Red	23	0.20	-0.69	-0.61	11
Green	19	0.21	-0.74	-0.59	21
Blue	12	0.12	-0.84	-0.76	10
White (background)	75	0.51			

A1.2.8 Questionnaires

For the two environments and after completing each visual task, subjects were asked to report their stress using a visual analogue scale (VAS) and to report their Affect levels using the positive and negative affect schedule (PANAS) [59-61]. PANAS short form [42] was used which can be found in the Appendix. Subjects were asked to evaluate five negative and five positive affects using 5-point Likert scales, whereby one indicates “Not at all” and five indicates “Extremely”. Five-point Likert scales using semantic bipolar words were used for a total of 12 questionnaire items related to visual perceptions and were selected based on the literature (Table A1-3).

Table A1-3. Questions used in the luminous environment subjective assessment

Parameter		Question	Bipolar descriptions	References
Visual-quality perception	Details	The words on the coloured chart were	Blurry---Sharp	[3, 21, 45, 62]
	Contrast	The contrast of the coloured task was	Low---High	
	Colours	How would you describe the colours in the room?	Faded---Strong	
		The overall variety of colours in the room was	Low---High	
Perception of the lighting appearance	Colour temperature	The lighting in this room feels	Cool--Warm	
	Brightness	I perceive the space lighting to be to be	Dark---Bright	[1, 2, 63]
	Distribution	How the lighting distribution in the room appeared	Uneven --- Uniform	[1, 63]
Perception impressions of the room	Pleasantness	I perceive the room as a whole to be	Unpleasant ---Pleasant	[1, 2, 13, 64, 65]
	Interest	I perceive the room to be	Dull ---Interesting	[2, 13, 64, 65]
	Complexity	I perceive the room as a whole to be	Simple ---Complex	[13, 65]
	Excitement	I perceive the room as a whole to be	Tense---Calm	[2, 13, 65]
	Spaciousness	I perceive the room to be	Narrow ---Spacious	[2, 3]

Two additional questionnaires were used in the experiment for the reported presence [66] and Simulator Sickness Questionnaire (SSQ) [67]. The presence questionnaire was used after the subject had completed both test conditions (i.e., real and virtual) on three parameters (realness, spatial presence, and involvement) [11, 13, 66] in comparison to the real environment (Table A1-4). The SSQ was completed twice before and after immersion in the virtual environment to assess any physical discomfort associated with the immersion in the virtual environment. The methodology workflow and the several steps used to in this study are summarised in Figure A1-10.

Table A1-4. Reported presence questionnaire

Parameter	Statement	Bipolar descriptions
Realness [11, 13, 66, 68]	Your experiences in the virtual environment were consistent with your real-world experiences	Fully disagree—Fully agree
Spatial presence [29, 34, 78, 80]	I felt "being there" in the virtual environment	Fully disagree—Fully agree
Involvement [29, 34, 78, 80]	The virtual space has become reality for me	Fully disagree—Fully agree

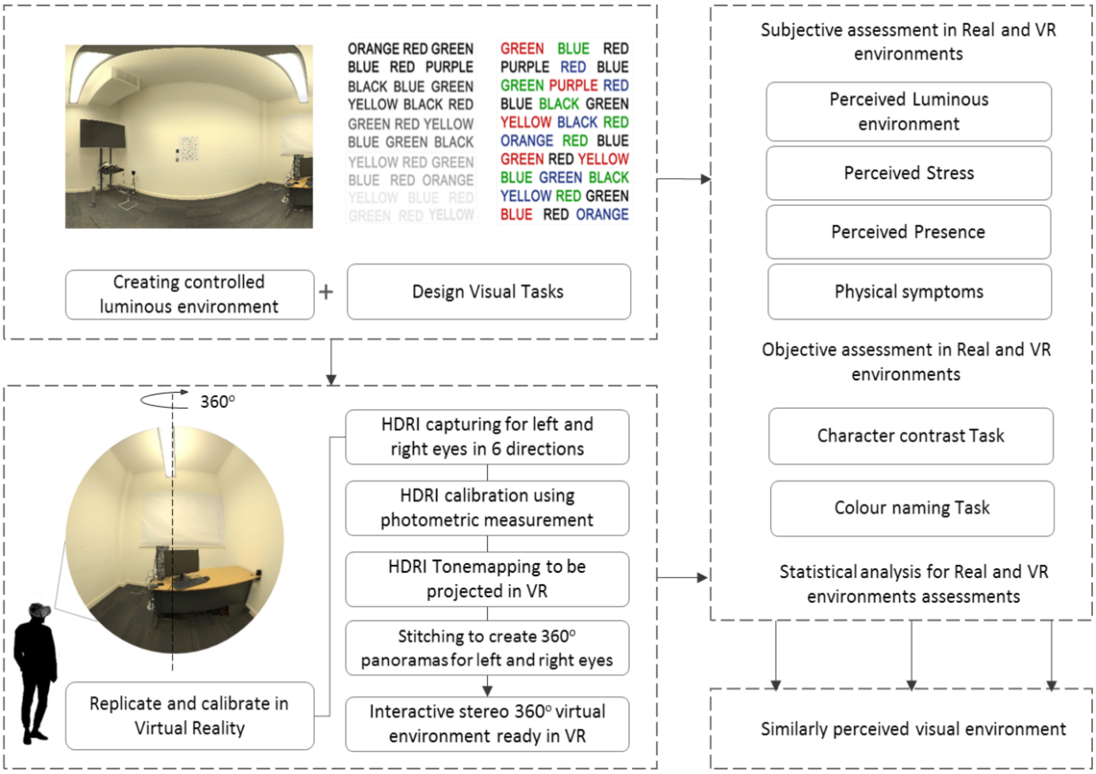


Figure A1-10. Illustration of the methodology workflow used in the experiment setup design

A1.3 Experiment Design

The study used a repeated measure design with the same participant taking part in two conditions to reduce random variability in the collected data [18]. The visual representation environment was the independent variable with two conditional variables: real environment and immersive 3-dimensional environment. The subjects were randomly assigned to test order to counterbalance the effect of presenting order of the stimuli between participants [18].

A1.3.1 Experimental Procedure

The experimental procedure and questionnaires used in the study were assessed and approved by the University of Nottingham Ethics Committee. A total of 20 subjects voluntarily participated in the test. The sample was recruited from Energy Technologies Building and Engineering Faculty from the University of Nottingham using online advertisements.

The experimental procedure and duration are shown in Table A1-5. At the beginning of each session, subjects read the experimental instructions and signed a consent form. Afterwards, subjects completed the post-experiment questionnaire on demographic information (age, gender, and academic background), vision problems (e.g., colour blindness), and vision correction, followed by SSQ on physical symptoms.

Subjects were undergraduate and postgraduate students, 10 males and 10 females with mean age of 26 years (SD= 6.24) and were from different ethnic backgrounds. None of the participants reported any colour vision problems and eight participants wore corrective glasses during the experiment. Only subjects who did not have epilepsy or suffer from migraines, motion sickness, dizziness, or sleep disorders were permitted to participate. An explanation of the tasks was given to the subjects, using samples with different versions of the tasks used in the experiment, before starting the experiment counterbalancing errors that could occur by unfamiliarity with the test [21]. Each session lasted approximately 40 minutes.

Table A1-5. Experiment detailed procedure and duration

Time progress in minutes	Activity	Duration in minutes
0-10	Welcoming and introduction, signing the consent form and completing the pre-test participant questionnaires and SSQ	10
10-12	Demonstration of the experiment to make sure subjects understand the procedures	2
12-17	Participant complete the task in the first environment and the experimenter record responses	5
17-22	Participant complete perception questionnaires and SSQ in case of VR	5
22-27	Participant rest outside the experiment room and experimenter prepare for the second condition	5
27-32	Participant complete the task in the second environment and the experimenter record responses	5
32-37	Participant complete perception questionnaires and SSQ in case of VR	5
37-39	Participant complete presence questionnaire	2
40	The end of the experiment. The participant will be thanked for their time, led to the door and told they are free to leave	1

When the subjects started with the virtual reality condition, they were not given any prior information of the real environment to make sure they saw only the VR first. In both conditions, subjects were invited to set on a rotating chair (Figure A1-1) and were instructed to look around to explore the surrounding environment. Two minutes were allowed before starting the task performance to allow adjusting to the luminous environment and at least 90 % of chromatic adaptation to be reached, as suggested by visual studies [20, 69].

In the characters contrast task, subjects read a total of 45 characters, beginning from the top left corner. In the colour discrimination task, the procedure was repeated, but instead, they were asked to name the colours of the words. In both tasks, the number of words was the same but their position and the associated colour or contrast were randomly assigned to counterbalance any learning effects or errors related to the task design [18].

After completing each condition, participants were asked to complete the stress and PANAS questionnaire and a series of questions in random order regarding the perception of visual-quality, lighting, and impressions of the room resultant from the assessed luminous environment (Table A1-3). After the virtual condition, participants completed another SSQ. Subjects removed the VR headset to complete the questionnaires and were allowed to refer to the VR at any point of the questionnaire to help provide their responses. A similar procedure was followed when evaluating the real environment. Subjects were given a five-minute break between conditions and were asked to report their sense of presence in the virtual environment at the end of both conditions (Table A1-4). Before leaving, participants were asked to sign a consent form indicating the absence of any discomfort that might have been caused by the VR.

A1.4 Results

For visual task performance, no errors were found in both environments for characters contrast task, while colour naming errors in the Stroop task were only detected in the virtual environment. Hence, visual performance was analysed only by the time spent to complete the tasks, and colour naming errors were analysed separately. The subjective responses to different questionnaires were also analysed for the perception of visual-quality, lighting, and impressions of the room resultant from both luminous environments, SSQ before and after immersion in virtual reality, and sense of presence.

A1.4.1 Task Performance

In Figure A1-11, boxplots of the results show the outliers (circles) and the tendencies for the statistical values (e.g., 25th percentile, median, and 75th percentile) [70], indicating lower levels for rate of time for Characters Contrast (CC) and Colour Naming (CN) tasks in virtual reality environment. This suggests a higher rate of visual performance under the real condition.

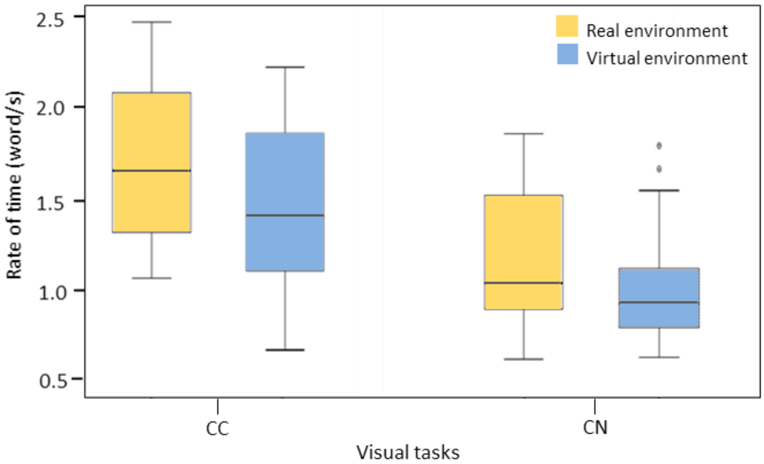


Figure A1-11. Boxplots presenting the rate of time for the two tasks in real and virtual environments.

To determine whether the mean average values were a reliable indicator of the data distribution, statistical tests (Kolmogorov-Smirnov and Shapiro-Wilk) and graphical plots (Q-Q) were used. The Levine's test was also applied to determine whether the variances in the data across the independent variables were homogeneous (i.e., approximately equal). When the assumptions of normality and homogeneity of variance were met, the mean average parameter was considered to be a reliable indicator of the data distribution [18]. When these assumptions were not met, non-parametric tests were used as the mean average parameter was not a reliable estimator of the data distribution [18, 71]. These tests were used to determine whether the differences in errors detected were statistically significant across the two conditions. The effect size *r* was reported along with statistically significant values to provide a standardised measure of the differences across the two conditions [70]. The interpretation of the effect sizes was derived using thresholds given in the literature:

‘small’ ($0.20 \le r < 0.50$), ‘moderate’ ($0.5 \le r < 0.80$), and ‘large’ ($r \ge 0.80$) effect sizes, respectively [72].

The results indicate a highly significant difference between CC task performance in the two environments. Task speed in the real environment was different than in virtual environment: ΔMean= 0.24, SD= 0.28, $t(19) = 3.88$, $p < 0.01$, $r = 0.65$ (moderate effect size).

For CN task, the non-parametric Wilcoxon Signed-Rank test was used to analyse the data as the assumption of normal distribution of the data was violated. Similar to CC, the results for CN indicate a highly significant difference in task performance across the two environments. Task speed in the real environment was different than in virtual environment: $\Delta M_{dn} = 0.19$, positive ranks= 4, negative ranks= 15, ties= 0, $z_{score} = 2.76$, $p < 0.01$, $r = 0.45$ (small effect size).

These results along with box-and-whisker plots (Figure A1-11) provide evidence that the difference in task performance was moderately significant in CC and weakly significant in CN as participants needed more time to complete the same task in the virtual condition.

For CN task, errors were found in virtual environment condition (M= 2.63, SD= 2.11). No errors were detected in the real environment, which implies there may have been a difference in colour perception within the virtual environment. The initial analysis during pilot testing of CN in the virtual environment revealed that errors were made between the black and blue colours. This might be affected by the low resolution of the VR (i.e., with the characters size at similar RGB for the real task, participates were not able to clearly distinguish between those colours in the VR. To investigate this, an additional experiment was conducted to explore whether the tone-mapping or the limited resolution of the VR have affected the colours discernment of the virtual environment represented here by the task characters (i.e., to understand whether a change in colour discernments applies for larger targets or only a result of combined low resolution and small details). Participants were invited to perform simple CN in real and virtual conditions using different widths of strokes with the same character height and identical colours and tone-mapping process of previous test (Figure A1-12). The same experimental setting and procedure was followed. It was found that participants made no errors in the real conditions; contrary to the virtual one. In the virtual condition, participants were able to name colours correctly up until the 4th row with the same width size used in the previous experiment (Stroop task described in section A1.2.4). For the 5th row, errors were detected for all the colours that were presented.

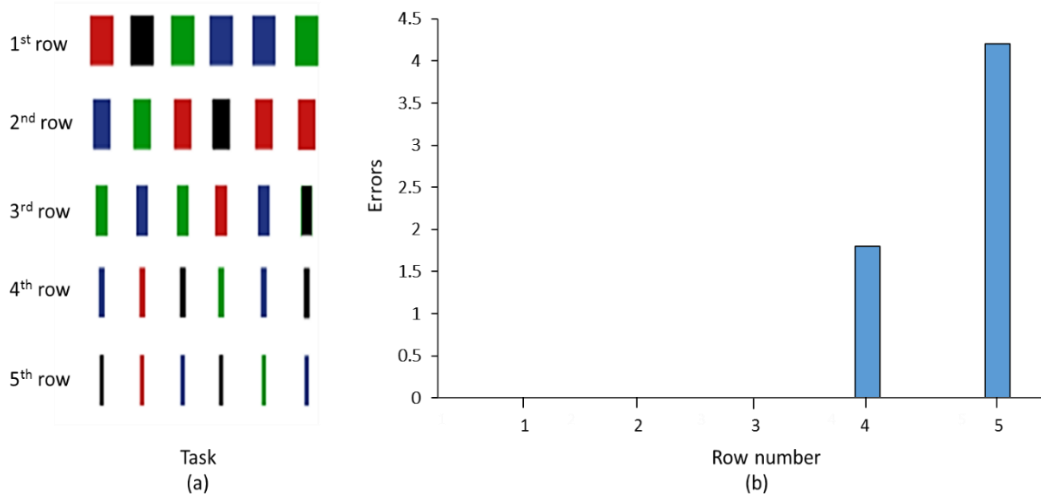


Figure A1-12. (a) Second colour discrimination task, (b) Mean numbers of errors detected

This provided evidence that the difference in CN performance may have been affected by the limited resolution impact on colour discernment of fine details. Both tasks indicate that the visual performance under a given luminous environment in terms of accuracy (freedom of errors) can be replicated in the virtual environment.

However, the task size should be carefully designed as the resolution was found to be affecting colours identification for fine details.

A1.4.2 Subjective Perception of Luminous Environments

Since questionnaires related to the luminous environment (i.e., presence and SSQ) were measured using ordinal scales, the non-parametric Wilcoxon Signed-Rank test was used to analyse the data. Table A1-6 presents the results of the Wilcoxon Signed-Rank test and effect sizes.

Three questions had statistically significant differences between the two environments for parameters: ‘Details’ (moderate effect size); ‘Contrast’ (moderate effect size); and ‘Colourfulness’ (small effect size). Colour variety was perceived similarly with no significant difference (tied ranks= 11). Although the contrast responses were lower in VR, the objective assessment of the contrast task showed no difference in accuracy in CC task (i.e., no errors were made in both environments).

Visual information was correctly extracted; however, it was slower in the virtual environment (i.e., more time was needed to complete the task in virtual condition). These questions were related to visual-quality perception of the scene. Other perceptual aspects of the luminous environment including perception of the lighting appearance and perception impressions of the room were perceived similarly in both environments.

Table A1-6. Results of the Wilcoxon Signed-Rank test for responses to questions.

Parameter	VR (M_{dn})	R (M_{dn})	*p*-value	Negative	Positive	Ties	Z_{score}	Effect size *r*
Brightness	4	4	0.57 n.s.	3	6	11	-0.59	-0.09
Distribution	4	4	0.58 n.s.	5	4	11	-0.58	-0.09
Colour Temp.	3	3	0.10 n.s.	10	4	6	-1.66	-0.26*
Pleasantness	3	3	0.27 n.s.	8	4	8	-1.11	-0.18
Interest	2.5	2.5	0.61 n.s.	3	5	12	-0.51	-0.08
Excitement	3	3	0.62 n.s.	5	4	11	-0.49	-0.08
Complexity	2	3	0.10 n.s.	3	7	10	-1.65	-0.26*
Details	2	4	0.00***	19	1	0	-3.84	-0.61**
Contrast	2	4	0.00***	15	1	4	-3.54	-0.56**
Colourfulness	2	3	0.01**	13	3	4	-2.53	-0.39*
Colour Variety	2.5	3	0.80 n.s.	5	4	11	-0.25	-0.04
Spaciousness	2.5	3	0.11 n.s.	6	2	12	-1.61	-0.26*

VR= Virtual environment and R= real environment
p-values: ***highly significant; **statistically significant; * weakly significant; n.s. not significant
Effect size: *** Large; ** Moderate; *Small

Regarding lighting appearance, no significant differences were found for brightness and distributions. For many variables, the comparisons showed no large differences across the two conditions as indicated by the higher number of tied ranks in Table A1-6. However, colour temperature results indicate a tendency towards the negative scale (cool). Questions on lighting high-order perceptions were perceived similarly with ‘small’ or ‘negligible’ effect sizes. Pleasantness, interest, and excitement demonstrated a considerably high number of tied ranks (i.e., no differences across the two groups), 8, 12, and 11, respectively. Complexity and spaciousness were perceived slightly different with small effect size, with 10 and 12 tied ranks.

In summary, the differences in lighting appearance and high-order perceptions were not statistically significant, and generally, the effect sizes were of a ‘small’ or ‘negligible’ magnitude.

A1.4.3 Reported Sense of Presence

The attributes of presence: realness, spatial presence, and involvement were measured using ordinal data with 5-point Likert scales; however, the mean and standard deviation along with percentages will be reported to allow comparisons to be made with previous studies. 75% of the 20 participants reported in the positive scale that they felt being there in the virtual environment (Mean= 3.74, SD= 0.99) and that their experience in VR was consistent with real-world (Mean= 3.40, SD= 0.89). 70% reported in the positive scale that virtual environment moderately became a reality for them (Mean= 3.21, SD= 0.91). These results are similar to those reported in literature [13, 73], which suggests that the used methodology provided an acceptable immersive environment in VR compared to the real environment and that participants had sense of presence during the virtual environment.

A1.4.4 Reported Simulator Sickness Symptoms

Wilcoxon Signed-Rank tests were used to analyse the reported simulator sickness symptoms (Table A1-7). The following symptoms were significantly different before and after using the VR: ‘General Discomfort’, ‘Eye Strain’, ‘Difficulty Focussing’, ‘Fullness of the Head’, ‘Blurred Vision’, ‘Dizziness Eyes Open’, ‘Dizziness Eyes Closed’, and ‘Vertigo’, with small effect sizes.

Table A1-7. Results of the Wilcoxon Signed-Rank tests for responses to questions of the simulator sickness questionnaire

Parameter	VR (M_{dn})	R (M_{dn})	*p*-value	Negative	Positive	Ties	z_{score}	Effect size *r*
General Discomfort	1	1	0.01**	0	7	13	-2.65	-0.41*
Fatigue	1	1	0.66 n.s.	2	3	15	-0.45	-0.07
Headache	1	1	0.56 n.s.	1	2	16	-0.58	-0.09
Eye Strain	1	1	0.01**	0	7	13	-2.53	-0.40*
Difficulty Focussing	1	1	0.01**	0	7	13	-2.53	-0.40*
Salvation Increasing	1	1	0.41 n.s.	1	2	17	-0.82	-0.12
Sweating	1	1	1.00 n.s.	0	0	20	0.00	0.00
Nausea	1	1	1.00 n.s.	1	1	18	0.00	0.00

Difficulty Concentrating	1	1	1.00 n.s.	1	1	18	0.00	0.00
Fullness of the Head	1	1	0.05*	1	6	13	-1.93	-0.31*
Blurred Vision	1	1	0.10 n.s.	0	3	17	-1.63	-0.26*
Dizziness Eyes Open	1	1	0.08 n.s.	0	3	17	-1.73	-0.27*
Dizziness Eyes Closed	1	1	0.10 n.s.	0	3	17	-1.63	-0.26*
Vertigo	1	1	0.16 n.s.	0	2	18	-1.41	-0.22*
Stomach Awareness	1	1	1.00 n.s.	0	0	20	0.00	0.00
Burping	1	1	1.00 n.s.	0	0	20	0.00	0.00

VR= Virtual environment and R= real environment
p-values: **statistically significant; * weakly significant; n.s. not significant
Effect size: *** Large; ** Moderate; *Small

General discomfort may have been reported differently because most participants were using VR for the first time. In previous studies [13, 74], similar findings were reported for eye strain and dizziness. Nevertheless, it should be noted that all reported symptoms were denoted by small effect sizes and a high number of ties (tied ranks >13) for all symptoms, in other words, when the evaluations across both conditions were the same. Although these symptoms have been associated with virtual reality application, they are generally minor and short-lived [74]. In fact, before leaving the experiment setting, all participants reported that any discomfort that was experienced during the VR trial has subdued.

A1.4.5 Perceived Stress After the Task Performance

The Wilcoxon Signed-Rank test was used to analyse the data. Similar levels of stress were reported in both environments after completing the tasks. The results indicate no significant difference in PA and a minor increase in NA and VAS stress in VR with small magnitude (Table A1-8). This indicates that the use of VR alone does not impose any change in the post-task stress towards the positive direction (i.e., less stress) [75], and implies that any change in stress levels in the virtual environment may also be experienced in the real one.

Table A1-8. Results of the Wilcoxon Signed-Rank tests for responses to stress and PANAS scale

Parameter	VR(M_{dn})	R(M_{dn})	*p-value*	Negative	Positive	Ties	z_{score}	Effect size
Stress	29.50	17.50	0.04*	7	12	1	-2.095	**-0.33***
PA	16	16.50	0.06 n.s.	7	8	5	-0.057	-0.01
NA	6	5	0.17 n.s.	4	10	6	-1.380	**-0.21***

VR= Virtual environment and R= real environment
p-values: * statistically significant; n.s. not significant
Effect size: *** Large; ** Moderate; *Small

A1.5 Discussion

The results of this study show relatively similar subjective and objective visual responses between the real and virtual environments and provide evidence that the virtual environment could be considered as an alternative method when investigating visual responses.

Comparisons of subjective measures across the real and virtual environments (i.e., pleasantness, interest, excitement, and complexity) showed no statistically significant differences with small or negligible effect sizes. These findings support those found in a previous study [13]. The difference in perceived spaciousness of the room was also not statistically significant and had a small effect size. This parameter was not included in other representation media (i.e., 2-dimensional screen and 2-dimensional interactive panorama [3]), which suggests that a satisfactory representation of size perception could be produced in the virtual setting.

Participants were able to give correct responses when performing visual tasks presented in the virtual environment, albeit with a slower rate of time. The visual information is acquired from the scene based on its shape, contrast, and colour [53]. Hence, even with the lower resolutions as those provided by VR, the overall appearance of the scene can still be correctly perceived. For fine details, the low resolution has more impact and subjects need more time to perceive the visual information. This was confirmed during the debriefing session.

While commenting on their experience in the virtual environment, participants stated that it felt like looking through “fuzzy glass into the actual room” and that they were “aware of the small squares forming the lens”. This may indicate a limitation of the currently available VR lenses and their resolution. This was also reflected in their response to questions regarding the quality of the scene (i.e., contrast, colourfulness, and details). The contrast ratios between the two environments were acceptable and had no effect on the accuracy in character contrast task as participants had no errors in reading different contrast ratios. However, the low resolution did impact their performance on colour naming for some colours and the follow-up test showed that the applied method can replicate the colours in the actual environment, as perceived colours of the entire scene. However, this is not true for some colours in the case of fine details.

Another limitation of the discussed method in this study is the difference in luminance values between the real and virtual environment due to the limited luminance that can be produced with similar types of displays (~216 cd/m^2) [43] and to approximately 118 cd/m^2 with the used software [56] in this study, as calculated in the response curve indicated in section 3.2.5.1. This restricted the use of this technology when considering the evaluation of glare caused by high luminances and enforced the use of tone-mapping process. As HDRI images cannot be directly displayed in the VR scene, their dynamic range must be compressed to the dynamic range of the display. Hence, the selection of the tone-mapping operator is essential and unbiased objective selection of different parameters such as contrast and colourfulness as proposed in this study should be used in order to replicate the results, as both affect the preference of presented scenes [45, 46].

The three attributes of presence: realness, spatial presence, and involvement, respectively, showed fairly acceptable results compared to previous studies [13, 73], which indicate that the used methodology was adequate to create an immersive environment and that participants had a sense of presence within the virtual environment.

General discomfort, eye strain, and difficulty focussing were slightly higher after using the VR. General discomfort was reported differently as a result of non-familiarity with the technology, as indicated by the subjects at the end of the experiment. In previous studies [13, 74] similar findings were also reported. Although the effect was minor for all symptoms ($0.20 \leq r < 0.50$), future studies should consider these effects (for example, allow participants to familiarise themselves with the device prior to the main test).

Similar levels of post-task stress using VAS and PANAS scale were reported in both environments. However, the self-reported stress and PANAS scale results were not consistent, a minor increase in stress was reported in VAS with less magnitude in PANAS. Hence, objective measures are encouraged to be used along with previous scales to assess stress and effect levels, such as biofeedback [76-79] and eye-tracking [80-82] technologies.

A1.6 Conclusion

In this study, a novel method for evaluating the use of immersive virtual environments as a replacement of real luminous environments was introduced using a physically-based 360° imaging technique. Objective tasks performance was conducted and subjective responses to the perception of scene visual-quality, lighting, and personal impressions of the same test-room were collected along with presence and physical symptoms questionnaires to compare the virtual to the real environment.

The main findings of this study are:

- Participants took relatively longer time to complete the same visual tasks when using VR than when it was presented in the real environment.
- The subjective assessments showed no significant difference for the perception of the lighting and the perception impressions of the room between the two environments.
- A significant difference was found in visual-quality attributes assessment (i.e., details, contrast, and colour vividness). Nevertheless, the analysis of contrast task and colour naming tasks indicated that both colours and contrast replications were acceptable. Hence, the responses may be affected by the limited resolution of the current VR headset.
- The use of VR had minor effects on reported physical symptoms and produced similar stress and positive and negative affect levels, which indicate the adequacy of the proposed methods; however, a more objective assessment could be used in future studies to accurately measure the stress, positive and negative affects, and high order light perceptions.

These findings were based on objective and subjective evaluation of twenty participants. A similar number of participants have been used in lighting research [83,84], and the results were statistically relevant and were interpreted based on a more conservative approach (i.e., reporting the effect sizes as an additional measure for significant difference along with *p*-values); yet, some caution should be acknowledged when trying to generalise these research findings.

These results encourage the enhancement of the VR lens technology as the result of this study along with the mobility of the used device has a promised outcome that can replace the continuously changing real daylit environment.

In conclusion, the proposed method looks promising as an alternative to investigate real luminous environments and guarantee reproducibility of the experiment. Further studies on more levels of the investigated parameters (i.e., brightness, colour temperature, etc.) are encouraged to add more validity to the used method. The development of VR headset with higher resolution and HDRI screens could benefit more attributes of lighting to be studied (e.g., glare); however, it is yet to be developed.

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Appendix A1-1

PANAS and self-reported stress

Please draw a vertical line at the appropriate point along the Visual Analogue Scale (VAS).

'Indicate how stressed you feel

0	50	100
Not at all		very stressed

On scale from 1 to 5 please circle how you feel at this moment using the reference scale

1	2	3	4	5
Not at all	a little	moderately	quite a bit	extremely

Active	1	2	3	4	5
Attentive	1	2	3	4	5
Inspired	1	2	3	4	5
Alert	1	2	3	4	5
Hostile	1	2	3	4	5
Afraid	1	2	3	4	5
Nervous	1	2	3	4	5
Determined	1	2	3	4	5
Upset	1	2	3	4	5
Ashamed	1	2	3	4	5

Appendix A1-2

Participant Information Sheet

Project Title: Evaluating Visual Performance in Different Luminous Environments

Researcher: Fedaa Abd-Alhamid [laxfa10@nottingham.ac.uk]

Supervisor(s): Dr. Yupeng Wu [Yueng.Wu@nottingham.ac.uk], Dr. John Calautit, and Dr. Peter Rutherford

Advisor: DR. Michael Kent

Thank you for agreeing to take part in this research study about evaluating visual response in different luminous environments. Before you begin, we would like you to understand why the research is being done and what it involves for you. We would like to remind you that this study optional and it is up to you to decide whither to take part. If you do decide to take part, you will be asked to sign a consent form. Following this, you will be asked to fill out an initial questionnaire to collect some basic information about yourself including demographic information (age, gender etc.) and simulator sickness questionnaire.

The researcher will then lead you into a test room where you will be exposed to different environments (a virtual environment and a real environment). You will be asked to complete two tasks during each environment including reading a grayscale chart out loud and stating the colours of words of charts on the wall. After each test environment you will be asked to fill out a questionnaire followed by five-minute break before taking the next test environment. Once all environments have been viewed, you will be asked to fill out a final questionnaire comparing the virtual environments to the real world.

The Study purpose

The purpose of this study is to evaluate visual response in different luminous environments. You have been invited because you meet the criteria the researchers of this project are looking for participants:

i. Above the age of 18.
ii. Speak fluent english.
iii. Willing to view a virtual reality environment using head mounted display.
iv. Who do not have any neurological disorders (e.g., epilepsy).
v. Who do not suffer from migraines, motion sickness, dizziness or sleep disorders.
vi. Who are not visually impaired (e.g., glaucoma).
vii. Who do not have colour vision defects (e.g., colour blindness).

Will the research be of any personal benefit to me?

You are voluntarily participating in this study. We cannot promise that the study will help you personally, but the information we get from this study may help gain a better insight for Architectural research. This could help to make better design decisions in the future and improve the quality of architecture being produced.

Are there any possible disadvantages or risks in taking part?

When using virtual reality, there is a risk that you might experience "simulator sickness". It involves symptoms similar to those of motion-induced sickness, although simulator sickness tends to be less severe in virtual head mounted display and to be of lower incidence. People who suffer from epilepsy, migraines, motion sickness, dizziness, sleep disorders or blurred vision are more likely to experience adverse effects, so please do not take part in the study if you suffer from any of these conditions. If you experience any symptoms during the session, or any other discomfort, please alert the investigator immediately, or you can simply remove the headset yourself, like you would a pair of googles.

What will happen to the information I provide?

We will follow ethical and legal practice and all information will be handled in confidence. The data collected for the study will be looked at and stored by authorised individuals from the University of Nottingham who are organising the research. They may also be looked at by authorised people from regulatory organisations to check that the study is being carried out correctly.

What if there is a problem?

If you have any queries or complaints, please contact the student's supervisor investigator in the first instance.

What if I have other questions?

If you have any questions or concerns, please do not hesitate to ask. The researcher can be contacted before and after your participation at the email address above.

Participant Consent Form

Project Title: Evaluating Visual Performance in Different Luminous Environments

Researcher: Fedaa Abd-Alhamid [laxfa10@nottingham.ac.uk]

Supervisor(s): Dr. Yupeng Wu [Yueng.Wu@nottingham.ac.uk], Dr. John Calautit, and Dr. Peter Rutherford

Advisor: DR. Michael Kent

I the undersigned as research participant confirmed that (please sign your initials as appropriate)

☐ 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 do not suffer from any of the following: epilepsy, migraines, motion sickness, dizziness, sleep disorders or blurred vision.

☐ 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, and that digital data will be stored only on a password-protected computer and on a secure server. Only researcher 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 supervisor and the supervisor 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 ……………………………...… Date …………………………………

Signed ………………………………………………………… (Researcher)

Print name …………………………….…… Date ………………………………….

Post Study Participant Consent Form

Project Title: Evaluating Visual Performance in Different Luminous Environments

Researcher: Fedaa Abd-Alhamid [laxfa10@nottingham.ac.uk]

Supervisor(s): Dr. Yupeng Wu [Yueng.Wu@nottingham.ac.uk], Dr. John Calautit, and Dr. Peter Rutherford

Advisor: DR. Michael Kent

I the undersigned as research participant confirmed that (please sign your initials as appropriate)

☐ Any feelings of discomfort I may have felt during the trials have subsided.

☐ I have been advised to wait for approximately 30 minutes between completing the simulator trial and driving

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

Print name ……………………………..… Date …………………………………

Signed ………………………………………………………… (Researcher)

Print name ……………………………..…… Date ………………………………….

Contact details:

Researcher: Fedaa Abd-Alhamid [laxfa10@nottingham.ac.uk]

Supervisor: Dr. Yupeng Wu [Yueng.Wu@nottingham.ac.uk]

Pre-Test Subject 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, are you using glasses or contact lenses to correct any eye conditions?
□ Yes □ No
6. What is your ethnic background?
□ White □ Mixed / Multiple ethnic groups □ Asian
□ Black / African / Caribbean / Black British □ Other ethnic group ______
7. What is current state of health? □ Ill □ Not too bad □Good
8. 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.

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Appendix A2

Paper 2: Evaluating the Impact of Viewing Location on View Perception Using a Virtual Environment

Evaluating the Impact of Viewing Location on View Perception Using a Virtual Environment

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Abstract

Window views are important design features in buildings. Views can impact the cognitive attention, psychological and physiological well-being of building occupants due to their ability to provide recovery in stressful working environments. The impact of viewing position on view perception as a result of the visual parallax effect resulted from occupants seeing a window from different relative positions in any given room has not been comprehensively investigated. In this study, view perception was evaluated using a physically-based 360^{o} virtual environment at three different viewing locations: close, middle, and far. The three conditions were presented to thirty-two participants. The study employed a comprehensive method by collecting subjective and physiological evaluations. A stress-recovery methodology to assess restorativeness effects was used by presenting a window view observing period after a stressful task was performed. Subjective assessments included questions on view restorative ability, view content and size preferences, view valance/arousal, and positive and negative affects. Physiological measures included skin conductance, heart rate, and heart rate variability. Results showed significant differences in subjective parameters and measures of skin conductance. Decreased view quality was reported as participants observed the view from the further viewing locations compared to the close position. The study highlights the importance of the informative content seen in the window view such as the sky and ground, which may impose limitations on recommended room depth and windows design. The results of this study show that the design of window views has important implications on the health and well-being of building occupants.

Keywords: Visual comfort; Virtual Reality (VR); View perception; View quality; Physiological assessment; Parallax.

A2.1 Introduction

The need for natural light, fresh air, and connection to the outdoor environment (i.e., time of day and weather conditions) are just some of the reasons why windows are an important feature in the design of any building [1, 2]. View and daylight are often seen as separate functions of the window. The view as to what is seen outside and the daylight as to the illumination transmitted inside the building. However, views could be considered as the perceived visual messages perceived by the human perceptual system that are transmitted into the building using daylight [3, 4] (i.e., daylight reflected from outside surfaces carriers visual information and enters into the building through windows, which is perceived by building occupants as the view). Through this process, daylight could be referred to as a carrier of outdoor view.

View preference can have a profound influence on cognitive attention and performance [5-7] and on the psychological and physiological well-being [3, 6-9] of building occupants. Despite their known importance on occupant satisfaction in buildings, the visual connection provided by windows with the outdoor environment is not well understood [10]. Studies have mainly focussed their efforts on understanding the roles that view content (e.g. natural and urban elements) and horizontal stratification (e.g., the layering of view content) have on window view perception [2, 9, 11-15]. Other studies have evaluated the preferred size of the window that provides the view [11, 16-21]); nevertheless, studies have often shown inconsistent conclusions; for example, people reported different preferred window sizes in different studies (e.g., 35 % [16], 25 to 30 % [18], 50 and 80 % [17], 40 % [20], 100 % [21]).

Experiments would often use different methods of collecting subjective ratings of views from windows, and this may be one reason why studies found inconsistent results. Another reason might be the fact that these studies are only relying on subjective ratings, which are often prone to methodological biases [22]. The experimental setting in different window view studies has also varied; some studies used 2-dimensional representation methods [14, 15, 23, 24], while in other cases, reduced-scale models using fixed viewing positions [16-19] were utilised. Both approaches have not considered dynamic changes when observing windows. The dynamic criterion relates to the observer's viewing position relative to the window, which changes the amount of view that is visible or blocked by adjacent walls [11]. This dynamic criterion of visual perception for the relative position of objects is known as movement parallax [25, 26-28].

As a result of this parallax, window-view relationship changes and objects at different vertical layers (i.e., depths) or a certain location within the view change their relative position when an observer changes their position. The change in distance from the window will also result in relative changes in view, whereby at closer viewing positions, the window area appears larger and more content is visible. The view content will also look larger since more distant objects occupy smaller angles across the retina than closer objects, and thus, relatively appear smaller when further away [27, 29]. This reduction in relative size is not linear, i.e., as the distance from the observer increases, change in relative size will occur with smaller magnitudes for the same displacement [29]. When an observer is positioned further away from the window, the aperture appears smaller and parts of the view in relation to the aperture edges cannot be seen, which are usually the most informative parts of the view providing information about the outdoor (i.e., the sky and the ground) [11]. This lost in visual information could offset the benefits of the view, implying that a good, informative, and satisfying view could impose limitations on room depth for a given window to wall ratio.

Previous studies indicated that windowless environments or having poor access to a window view (e.g., due to office furniture arrangement and seating positions) can increase levels of stress in buildings [7, 23]. Close proximity to the window is generally preferred by occupants [11, 30, 31], and studies have indicated that the distance at which an occupant is located from the window affects the self-reported levels of satisfaction [11, 32]. When occupants cannot be close to a view, they generally prefer to have a larger window [16]. Although it is not entirely clear why occupants desire window views, they offer psychological benefits by providing cognitive restoration and recovery [33]. The mechanism underlying the restoration and recovery has been explained by the attention restoration [34] and affective response [35] theories.

According to the attention restoration theory, when an individual is presented with fascinating stimuli (e.g., visual or auditory), this may involuntarily capture their mental attention and consequently promote cognitive psychological recovery [34]. By replacing the cognitive mechanisms responsible for direct attention, this creates a mental restoration that is experienced by an individual. Supportively, literature has shown that views of nature elements (e.g., greenery) modestly capture attention and promote cognitive restoration; while in an urban environment (e.g., built), attention is intensely captured and there is less cognitive restoration [5]. The affective response theory [35] states that stimuli of high interest elicit positive emotional responses, thereby promote sustained psychological attention and also reduce levels of stress. This theory has been used to explain the preference of natural environments over those with urban (built) content. Both theories indicate that when the perceived impression of a stimulus is positive, the following cognitive and physiological reactions induced will be also positive. Accordingly, this increases the ability to sustain attention, reduces levels of negative affect, and reduces physiological stress [36].

When linking these two theories back to how occupants perceive windows, it could be inferred that restorative benefits can be experienced when the view diverts their attention away from the stressful stimuli. This may decrease levels of stress [32, 35, 37], increase sustained attention and cognition [38-40] and could create healthy working environments that promote levels of work productivity. Also, the view content plays an important role in how occupants perceive the window, which can be explained in the Circumplex model of affect [41]. While environments that provide high arousal and low pleasure can lead to high levels of stress, high pleasure and lower arousal environments promote relaxation [39, 42, 43]. Lower arousal and pleasure levels result in a perception of dullness (i.e., less stimulating environments) [44].

The mechanisms underlying view perception as stress influencing factor are summarised in Figure A2-1.

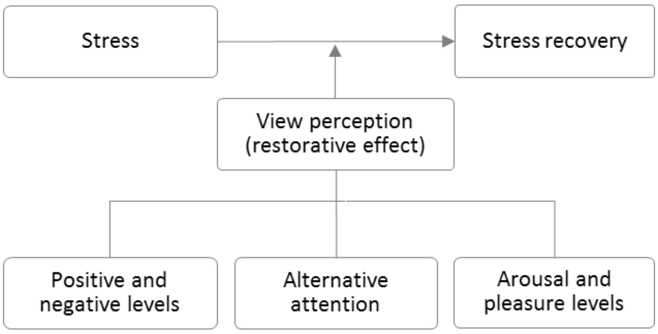

Figure A2-1: Summary of the mechanisms that promote the view as stress influencing factor

Because the view has a profound influence on both psychological (i.e., subjective ratings that appraise the visual content) and physiological (i.e., levels of stress) when a window is observed by an occupant, a multi-criteria approach that includes both types of measures is needed to quantify the differences in view perception. When considering the dynamic interaction between the window view and the relative viewing position of the occupant, there are strong reasons to believe that both measures will be needed to provide a comprehensive understanding (i.e., how occupants react to the view at different distances away from the window).

Stress levels can be measured using many physiological indicators including skin conductance (SC), heart rate (HR), and heart rate variability (HRV) [45, 46]. All three measures have been used to evaluate differences between different visual stimuli. HR decreased (i.e., showing signs of decreased stress levels) when engaging visual stimuli require cognitive attention were presented [47-49] and when the visual stimuli were considered to be fascinating or gave the feeling of being away (i.e., shift away from the present situation to a different environment) [50]. HR reflects the stress state of humans and can be further evaluated using HRV [45, 51] (i.e., changes in the time intervals between adjacent heartbeats [52-54]).

HRV can be separated into four frequency bands: high frequency (HF-HRV) (0.15 to 0.4 Hz), which reflects relaxation; low frequency (LF-HRV) (0.04 to 0.15 Hz); the very low frequency (VLF) (0.04 to 0.003 Hz); and ultra-low frequency (ULF) (<0.003 Hz) [54], whereby the variability in any of the lower frequencies represents a mixture of stress and relaxation [45]. The ratio of LF to HF power (LF/HF) has been used as an indicator for stress level [54], whereby a higher ratio indicates elevated stress level and a low value indicates more relaxation [52, 55, 56].

SC measures sweat glands activity and consists of two components: phasic Skin Conductance Response (SCR) and tonic Skin Conductance Level (SCL). SCRs are associated with short-term events and occur in the presence of discrete environmental stimuli (e.g., visual or auditory) which usually show up as sudden increase (peaks) in the SC data; while SCL is used to measure continuous responses and represents the base level of SC [57]. SCR can increase when visual stimuli elicit amusement [58], pleasure and pleasantness [49], or attention and arousal [45]; while increased SCL indicates higher stress levels [45].

This study aims to develop a comprehensive method (including both subjective and physiological assessments) to evaluate the view perception from different viewing observing locations. To be more specific, this evaluation has been undertaken in a typical office room with a view that includes both natural and urban elements observed at three different locations in the room. A validated 3-dimensional virtual reality (VR) representation method [59] was adopted to determine whether the viewing position mattered in an experiment. This method displayed an office-like environment in an immersive VR setting, which was comparable to the original environment. This approach utilises stereoscopy vision to create depth perception in the VR setting [60] and, within a certain degree, can produce realistic visual contrast and colour properties

[59]. VR is also capable of providing a much higher degree of experimental control over parameters that would vary in buildings (e.g. temperature, noise, daylight, etc.), which is one of the main challenges in experimental studies using windows [20, 61]. Across different experimental conditions, the illumination levels can also be maintained in VR settings, which can affect the investigated visual stimuli perception if left uncontrolled [20].

Three research objectives were derived: (1) Developing a replica in virtual reality based on the physical and luminous conditions at three viewing locations: close, middle, and far from the window within an office room; (2) Collecting subjective responses on view quality parameters, including view restorative ability, view content and size preferences, view valance/arousal, self-reported stress, and positive and negative affects; and (3) measuring physiological markers, namely: SC, HR, and HRV. Objectives (2) and (3) were used to assess the differences in view perception at different viewing locations as seen within an office room replicated in the VR environment.

A2.2 Methodology

The methodology was designed to provide controlled luminous conditions to evaluate the subjective and physiological responses to the change in window view based on different observing locations within a virtual office room. The real experimental environment luminous conditions and the stressful task contrast properties were assessed to be replicated in the virtual environment. In this section, subjective evaluations and physiological apparatus and markers are explained, followed by the designed experimental procedure. The statistical tests used to analyse the data collected in this study are also described in this section.

A2.2.1 Experimental Environment

Controlled luminous conditions to evaluate the subjective and physiological responses were used to evaluate a virtual office room.

The virtual office was created by replicating an office room (test room) that was lit by both natural and artificial lighting. Using a validated approach [59], the physical and photometric conditions of the test room were presented within a VR environment. A virtual environment was considered appropriate for this study as opposed to relying on daylight from real windows, since photometric parameters would continuously change over time [62-64]. Other extraneous variables (e.g., temperature, humidity, and noise) could also be controlled in the test room.

The test room was located in the Energy Technology Building (University of Nottingham, UK) (Figure A2-2). The room had internal dimensions of 4.35 m x 2.85 m and a floor to ceiling height of 3.2 m (Figure A2-2). The internal surfaces of the room had reflectance (ρ) properties: $\rho_{wall} \approx 0.7$ for walls, $\rho_{floor} \approx 0.1$ for the floor, and $\rho_{ceiling} \approx 0.8$ for the ceiling, which were estimated using the Munsell values [65]. The office was located on the first floor and the view from the window is considered a neutral with mixed of urban and natural elements which would be considered by the green building practice guide BREEAM to be an adequate view [66]. The room had a double glazing window with 20 % window to wall ratio as it is recommended for rooms with depth ≤8 m [66], and the window had a 1:1 aspect ratio.

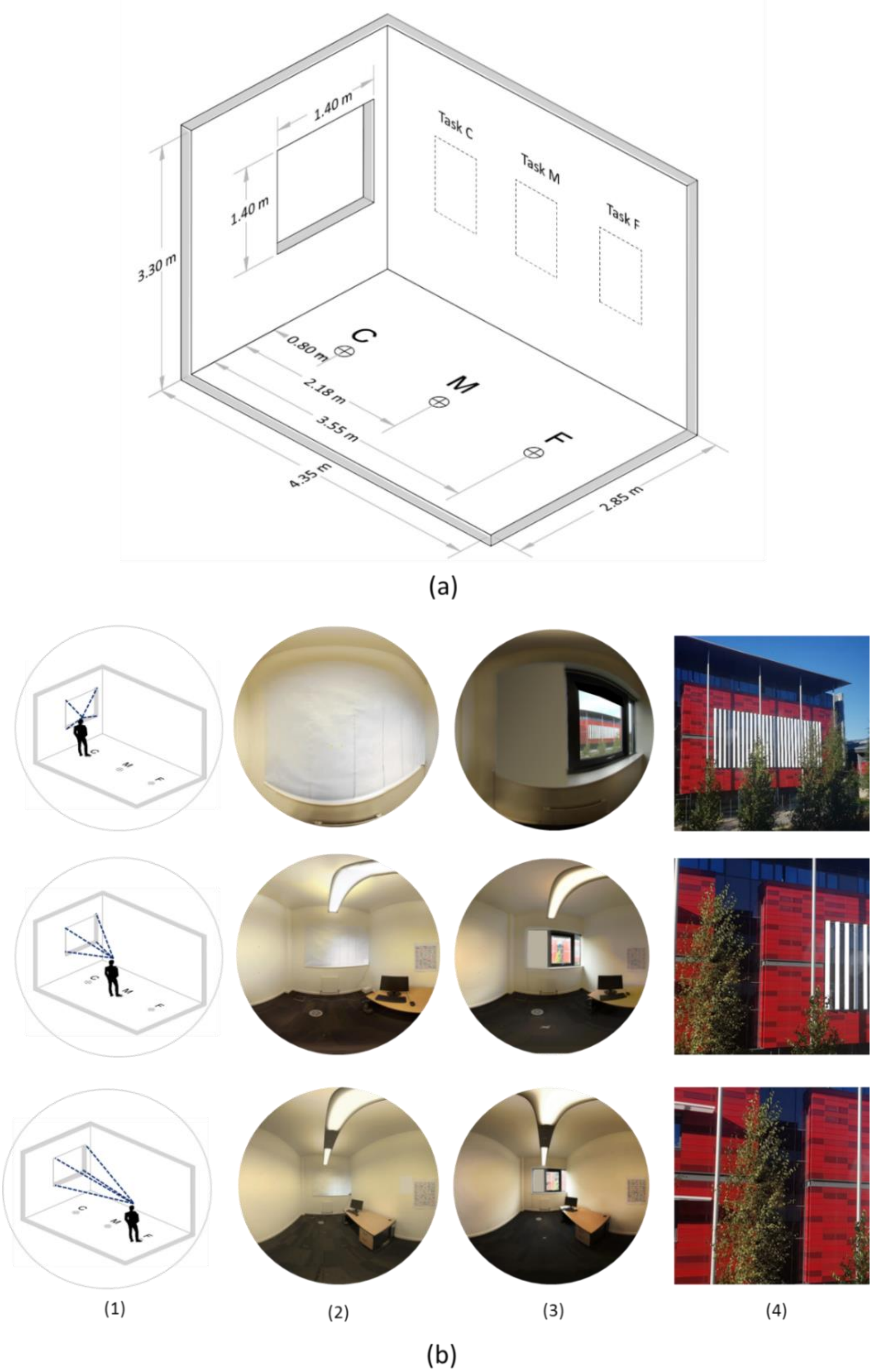

Figure A2-2. Image (a): The test room dimensions. Image (b): (1) Three observing locations; (2) the three windowless baseline environments; (3) the three environments with view indicating the view size in the visual field; (4) the corresponding view content for each location

The room contained furniture to resemble an office environment. A visual task was mounted onto a wall at 1.50 m from the viewer position at three different distances from the window: Close (C), Middle (M), and Far (F) (Figure A2-2(a)). The middle location was placed at the median value of the length from the window to the rear wall of the room, and the C and F locations were selected based on the minimum standards for office furniture [67], which allowed a 0.80 m space at both ends of the room. The same locations were replicated in the virtual environments.

A2.2.2 Stress Inducing Task (Stroop Test)

The proposed methodology to quantify the view used stress recovery as an indicator of view quality, which was measured by subjective and physiological responses. The Stroop test is a colour-word conflict test [68] and was selected for its ability to increase stress levels when the task is being performed [69-71]. The Stroop test can also be used as a neuropsychological tool in the assessment of cognitive work [70, 72] as it comprises of a selective attention feature (i.e., the process by which individuals focus on task-relevant information and ignore irrelevant distracting information [73], which usually occurs in office environments [74, 75].

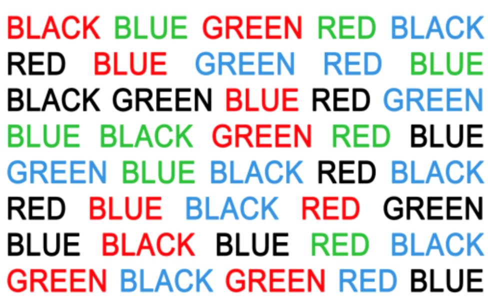

Figure A2-3. Example of the Stroop test used to elevate stress levels

The Stroop test (Figure A2-3) composes of a total of 15 rows with five words on each row for each task, and the text size was 20 mm creating a 0.76° angular size produced by character height, which is within the range needed for fluent reading (between 0.2 to 2°) [76]. Four colours: Red, Green, Blue (RGB), representing the three main components of the RGB colour model usually used in lighting studies [64, 77], and black were used in the Stroop test. The selected colours had the values of chromaticity as described in previous studies [59]. The words and colours were randomly allocated in three versions of the tests (for C, M, and F) to counterbalance any learning effect.

Subjects were instructed to name the colours of the words as fast as they can, attempting to name even the ones they were uncertain of. The Stroop test lasted 45 seconds [69]. Luminance values of the task were measured using Hagner S3 photometer and compared to those created in the counterpart virtual environments. This was used to elevate the stress levels to assess the view quality based on restorative effects (i.e., recovery from stress).

A2.2.3 Physically-Based Virtual Environment

To replicate the luminous conditions of the test room in the virtual environment, the following equipment were used: 1) Canon EOS 5D camera equipped with a fish-eye lens (Sigma 4.5 mm f/3.5 EX DG) mounted on a tripod; 2) Hagner S3 photometer with illuminance sensor; 3) Minolta Chroma-meter CL-200; 4) HTC-Vive headset. The camera was mounted on a tripod 1.5 m from the wall containing the visual task. To keep the window view at the centre of the participant's field of view in the VR setting, the camera was mounted 1.60 m from the floor. Lighting measurements were repeated three times at different distances from the window, corresponding to C, M, and F, respectively.

High dynamic range images (HDRI) were created by combining seven low dynamic range images (LDRI) with different exposure values [59]. Six virtual environments were created in this study. Three for the windowless neutral baseline conditions and three for window view conditions taken from the three different viewing locations [47]. The lowest sensitivity (ISO) 100 was used to reduce the noise in the HDRI with fixed white balance (i.e., correct colour temperature (CCT)) to maintain consistent colour space transitions [78]. A white balance of 4300 K was used, which was approximate to the average CCT in the room measured using the Chroma-meter CL-200 (accuracy ± 0.02 %). Across the three locations at the camera position, the CCT measured were: C= 4881, M= 4032, and F= 3851 K. The HDRI images were calibrated with point luminance measurements and were tone-mapped with 2.2 gamma and key value of 0.01 [79], which created similar contrast values to the real environment.

The images were taken in June between 11:00 am and 12:30 pm on a day under a mostly clear (but stable) sky condition. The room had a north facing window with no access to direct sunlight and was lit by artificial lighting in this period. The measured horizontal illuminance values taken from a height of 0.8 m from the floor [80] at the three viewing positions were: C= 1347, M= 709, and F= 491 lux.

The images were taken with a fish-eye lens covering 180^o in each direction from the same viewing position, aligning the entrance pupil axis to the rotation axis to minimise the differences between the various pictures composing the 360^o view [81]. The resultant six tone-mapped images were combined into 360^o panorama. To create the depth perception from 2-dimensional images, the previous process was conducted twice from two viewpoints 65 mm horizontally apart to reproduce the distance between the centres of the observer's eyes [82]. The same process was utilised to create interactive virtual stereoscopic images giving the observer the impression of being immersed within a 3-dimensional environment. HTC Vive head-mounted display [83] with a computer with two 2.40 GHz 4 core processors and NVIDIA GeForce GTX 1060 graphics card were used along with Whirligig software, which supports the display of stereoscopic images, to display the immersive 360^{o} images. The VR HTC Vive has a dual AMOLED 3.6'' diagonal screen with a resolution of 1080 x 1200 pixels per eye (2160 x 1200 pixels when combined) and provides 110^{o} nominal field of view.

A2.2.4 Visual Task Properties in the Virtual Environments

Luminance values of the actual task were measured using Hagner S3 Photometer and the contrast ratios for the Stroop task were obtained using Weber's formula (1) [84], which was calculated using the background luminance of the task (L_b) and target luminance of the visual characters (L_t).

$$C = (L_t - L_b)/L_b \qquad \text{Equation (4.1)}$$

Since current virtual head-mounted displays cannot display HDR quality images, the tone-mapping process to the images projected in the virtual environment was applied to correct the luminance and contrast values [59]. Table A2-1 displays the real and virtual contrast values of the Stroop tasks and the percentage change in contrast between the real and virtual environments across the three conditions.

The contrast ratios for the same colour are similar across the three locations in the virtual environments: Red (*M*=-0.47, *SD*=0.06); Green (*M*=-0.51, *SD*=0.08); Blue (*M*=-0.54, *SD*=0.14); and Black (*M*=-0.76, *SD*=0.07) with slightly lower contrast in the close location. This is important for the Stroop test to sustain the stress level induced by the task across the three different locations as different contrast ratios might affect the task difficulty; hence, influence the stress-induced level.

Table A2-1. Luminance and contrast values of the different colours used in the Stroop tasks

Colour	Real environment luminance (cd/m²)			Tone-mapped images relative luminance			Real environment contrast			Virtual environment contrast		
	C	M	F	C	M	F	C	M	F	C	M	F
Red	68	36	38	0.19	0.27	0.30	-0.75	-0.71	-0.60	-0.40	-0.50	-0.52
Green	68	38	37	0.23	0.23	0.28	-0.75	-0.69	-0.61	-0.41	-0.57	-0.55
Blue	43	32	29	0.19	0.18	0.28	-0.84	-0.74	-0.70	-0.40	-0.67	-0.55
Black	25	18	14	0.10	0.10	0.14	-0.91	-0.85	-0.85	-0.70	-0.81	-0.77
White (background)	269	123	96	0.30	0.54	0.62						
Average Percentage Error (%)										45	15	14

A2.2.5 Physiological Apparatus and Objective Assessments

To evaluate the participants' responses to the views and to evaluate stress levels during the experiment, SC, HR, and HRV were measured to assess the responses at the three locations.

When immersed in the VR setting, participants sat at the centre of the room on a rotatable chair with an armrest that was used to minimise hand-movement when the physiological measurements were taken. SC and HR were recorded using sensors connected to the Mind Media Nexus-10 MKII acquisition device and Biotrace software (Figure A2-4). The Nexus10 MKII device was attached to the back of the rotatable chair, which allowed flexible movement when the participant needed to change their view direction within the virtual environment. The device was wirelessly connected to a laptop for data collection. Both SC and HR data were sampled at 32 samples per second (SPS) rate. These signals can continuously monitor nervous system activity in terms of stress and recovery [35, 36, 85-87].

The SC and HR changes during the exposure to the window view and during recovery from stress were subtracted from baseline measurements in order for the physiological data to be standardised for each participant to allow the comparison between different experimental manipulations [45]. The baseline and following physiological recordings were taken while the participants are immersed in the VR. A detailed explanation of baseline measurements can be found in section A2.2.6.

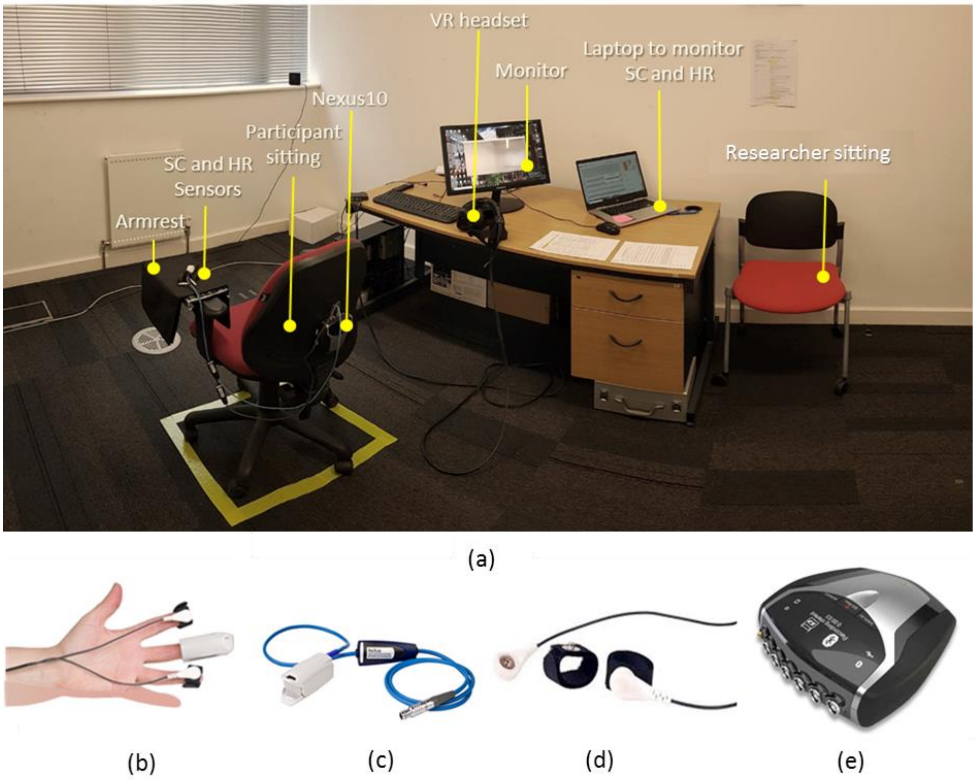

Figure A2-4. (a) The experimental setup; (b) sensors placement on participant's fingers; (c) HR sensor; (d) SC sensors; (e) Nexus10 MKII device. Note: The yellow square marks the viewing position during the experiment, which ensured that participants did not move outside this demarcated area.

During the experiments, the SC sensors measured the sweat gland activity of participants, which is regulated by the sympathetic nervous system reflecting states of heightened stress [45]. Ag-AgCL electrodes were attached to the distal phalanx of the index and ring fingers of the participants' left hand to measure skin conductivity –

expressed in microsiemens (μS – a unit of electric conductance) [57]. The HR sensor uses light-based technology to sense the rate of blood flow. Different measures of HRV, including LF-HRV and HF-HRV, can be acquired, which are expressed in milliseconds squared (ms^2) for different frequency bands. This sensor was connected to the middle finger of the participants' left hand.

Physiological responses were continuously collected during each session, and data at specific points of interest baseline, stress, and recovery was extracted [57, 88, 89] to identify the initial responses for discrete stimulus [45, 49, 87] (e.g., when participants observed the window view).

A2.2.6 Physiological Data Screening

The SC values were visually inspected to discard any data that was not considered to be reliably based on criteria recommended in the literature (e.g., sudden SC signal breaks) [57]. Four cases showed that the SC data may not be reliable to evaluate and were discarded from any further analyses. The SC data was imported from Biotrace and analysed using Ledalab V3.4.9 toolbox: a MATLAB-based analysis tool for extracting SCL and SCR values from the SC data, using a continuous decomposition analysis method [90, 91].

HRV data was directly acquired from the Biotrace software and the default criteria of automatic removal and correction of detected artefacts was used, in which if the difference between the adjacent inter-beat intervals was greater than 25%, it will be removed and replaced with interpolated data (i.e., an average value that is computed from the neighbouring normal inter-beat intervals). To accept the HRV value for further analysis, a minimum of 80% normal inter-beat intervals is required [89]. Accordingly, no value was identified from the HRV dataset. However, the excluded cases from SC data were also removed to have balanced sampled data sizes between the physiological measurements. The final sample size for the physiological data analysis was 28 participants; 22 males and 6 females with mean age of 29 years (SD= 6.24).

SCR data for the initial response of view observing was extracted using a response time of one to four seconds after presenting the window view with a minimum amplitude of 0.01 μS (i.e., minimum required shift in the signal to be counted as SCRs) [45, 57, 92]. Deflections (sudden shifts) in the signal that do not satisfy the threshold criteria are not counted as SCRs [88]. HR and HRV data for the initial response to the view was assessed using the mean data for the first 30 seconds of stimuli exposure. Measurements between 10 and 30 seconds were used to evaluate the observers' HR response to visual stimuli [15, 47, 50]. A respective baseline measurement was subtracted using similar response time of SCR and HRV to allow the comparison between experimental conditions [45].

The analysis of stress and recovery was performed using SCL and HRV measures. The changes in SCL and HRV were assessed using the first minute of recovery to measure the stress recovery from the first minute of exposure to the view (i.e., to measure the restorative effects caused by the exposure to view, which usually occur in short breaks taken by office workers). Respective baseline measurements (i.e., in the last minute of the baseline) were subtracted from recovery data to attain the change from the baseline. Physiological data of baseline and recovery is usually analysed over a time range between one and three minutes [35, 46, 70, 71]. Additionally, the SCL and HRV during the stress induction (45 seconds) were compared after being subtracted from the corresponding baseline values to explore stress level during the task performance at the three different locations in the office [46].

A2.2.7 Subjective Evaluations

View perception was assessed based on four aspects: view restorative ability, view content, size preferences, and view valance/arousal (see Table A2-2). Two questions related to daylight visual interest and complexity were also used. All questions were measured on a continuous scale ranging from, “Not at all” (= 0) to “Very much” (= 10). The continuous scale was explained to the participants during the experimental demonstration and they were reminded upon making their evaluation. Stress recovery was evaluated using the positive and negative affect schedule (PANAS) [93] and self-reported stress question, which were performed before and after completing the tasks.

Questionnaires were answered verbally, and the answers were recorded using Dictaphone which is more convenient when VR is used [47, 61]. The questions were randomised across the three conditions to eliminate any bias in subjective responses [94]. Reported simulator sickness symptoms produced from immersion in the virtual environment were assessed using the Simulator Sickness Questionnaire (SSQ) [95], which was completed at the beginning and the end of the experiment.

Table A2-2. List of the view perception questionnaire items used during the experiment

Parameter		Adopted to view Questions	Bipolar descriptors	Ref.
View restorative ability adopted from perceived restorativeness scale	Fascination	This view is fascinating	“Not at all” – “Very much”	[96-100]
		My attention is drawn to many interesting things in this view		
	Being away	Looking at this view would give me a break from the work routine		
		Looking at this view helps me to relax my focus on getting things done		

View content	I like the view provided by the window	[96-99]
View size	How satisfied are you with the amount of view in this space?	[19, 20, 23, 61]
View valance/arousal	How pleasant is the view? How exciting is the view?	[23, 47, 61]
View interest and complexity	How interesting is this view? How complex is this view?	

A2.2.8 Experimental Procedure

The study used a repeated-measure design with the same participant taking part in three conditions to reduce individual variability in the collected data [94]. The change in visual environment due to the distance from the view was the independent variable with three conditional variables: C, M, and F. The subjects were randomly assigned to test in order to counterbalance the effect of presentation order of the stimuli between participants [94].

The experimental procedure and questionnaires used in the study were assessed and approved by the University of Nottingham Ethics Committee. Subjects were either taught/research students or academic staff members and were recruited via posters and online advertisements. A total of 32 subjects from different ethnic backgrounds voluntarily participated in the experiment. Twenty-three were males and 9 females and the mean average age of the group was 28 years (SD= 6.08). None of the participants reported any colour vision problems, and 15 participants wore corrective glasses during the experiment. The study was conducted during summer months (July-

September) and indoor air temperature and humidity were measured in each session at the position of the participants.

The average temperature and humidity values measured inside the test room during the experiment were 22.3 ^{o}C and 49.1%. These remain relatively constant throughout the duration of the experiment, whereby indoor temperature varied between 19.0 ^{o}C (minimum) and 25.7 ^{o}C (maximum) and humidity between 42.4% (minimum) and 51% (maximum), respectively. Across the three test sessions, temperature and humidity also remained relatively constant, whereby the maximum differences (i.e., maximum minus minimum) recorded when considering all test sessions that participants had taken part in were 1.5 ^{o}C and 2.4%, respectively.

The experimental procedure and duration are shown in Figure A2-5 and detailed in the Appendix.

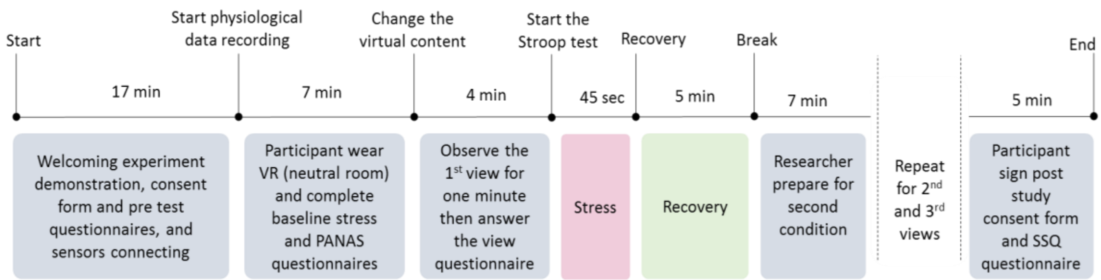

Figure A2-5. Overview of the experiment procedure from start to the end of a single test session

At the beginning of each session, subjects read the experimental instructions and signed a consent form. Afterwards, subjects completed a questionnaire surveying demographic and vision acuity information (e.g., corrective lenses and reported colour blindness) and completed the SSQ. Since the repeated-measure design minimises the influence of individual differences caused by variations in demographics, this helped to reduce the influence of age on physiological responses collected from subjects [45, 47, 101]. Participants were required to abstain from intaking caffeine eight hours and alcohol 24 hours prior to the test [102]. Those who suffer from epilepsy, migraines, motion sickness, dizziness, sleep disorders, or blurred vision were excluded from the study to avoid unwanted symptoms experienced from the VR setting [103]. Participants were not informed about the actual purpose of this study until the experiment had finished.

Upon arrival to the test room, participants were seated on the chair. The SC and HR sensors were connected, and their arm was rested on the chair armrest. This minimised hand movement and ensured that the signals were correctly recorded. Participants were asked to wear the VR to familiarise themselves with a baseline scene. When the participants were ready, they were asked to answer the Stress and PANAS questionnaire to be used as a subjective baseline. The physiological baseline measurements were then recorded for five minutes, which was more than the recommended two minutes [36, 49, 54, 88]. The virtual content was then changed to the view corresponding to the baseline environment (Figure A2-2) and participants observed the first view condition for one minute before answering the questions on view perception.

Participants performed the Stroop test for 45 seconds [69] followed by another five minutes of physiological measurements while observing the virtual window view. Participants then answered the stress and PANAS questionnaire again as a subjective measure of recovery. The participants were instructed to limit their hand movement and to remain silent during the baseline, recovery, and window view observation periods to limit the noise in the recorded signals [104], with the exception when they were answering the questionnaires. The same procedure was repeated until the three conditions were evaluated and participants were given a seven-minute break between each condition [87, 104] (Figure A2-5).

A2.2.9 Statistical Analysis

Statistical analysis was conducted to analyse subjective and physiological responses. The statistical test that was used to analyse the data depended on the data distributions and/or variances. The subjective data analysis was conducted for the full sample (n= 32), while the physiological data was analysed using pre-screened data from 28 participants. Physiological data was evaluated based on z-scores which is a recommended method to analyse physiological data [45, 105]. The original data was transformed to z-scores by subtracting the individual values from their sample mean and dividing this by the standard deviation.

To test the reliability of the questionnaires, that is, the survey items measured the same construct (i.e., view perception quality), the Cronbach's alpha (α) test [106] was used. The questionnaire had a high-reliability Cronbach's α= 0.94, attaining the accepted range (0.70-0.80) [106]. Hence, the collected questionnaire items measured the same construct.

Data collected from responses of view perception, reported stress, and PANAS was analysed using the repeated measures analysis of variance (ANOVA) test. For this test, the assumptions of normality and sphericity were assessed [94]. Sphericity refers to the equality of variances across repeated conditions (i.e., the variance between one pair could not be significantly different from another pair of conditions). Normality of the data about the mean was evaluated using the Kolmogorov-Smirnov [107] and Shapiro-Wilks [108] tests. When either assumption of normality or sphericity was violated, the non-parametric Friedman's ANOVA test was used [94]. When the assumption of sphericity was not met, Huynh-Feldt corrections were applied [104]. In order to determine which observing location was perceived differently from the other, pairwise comparisons were performed. To control the experimental-wise error rate, Bonferroni corrections were applied [94].

The effect sizes will be reported along with statistical significance values. The effect size is an inferential statistical parameter that can be derived from different statistical tests, providing a standardised measure of the magnitude of the difference and allowing comparisons among similar studies [106]. The effect sizes partial eta squared (η_p^2) and Pearson's r were estimated from the inferential tests. Interpretation of the effect sizes was inferred using "small", "moderate", and "large" thresholds recommended by Ferguson [109].

A2.3 Results

A2.3.1 Subjective Data

Figure A2-6 presents the results of subjective view perception. The y-axis shows the rating of view from 0 (Not at all) to 10 (Very much) by participants for different perception parameters displayed on x-axis when presented at different observing locations: C, M, and F. As indicated in Figure A2-6, the statistical parameters (mean, minimum, 25th percentile, median, 75th percentile, and maximum) tend to correspond to higher ratings of view perception when considering the eight parameters and when participants are closer to the window.

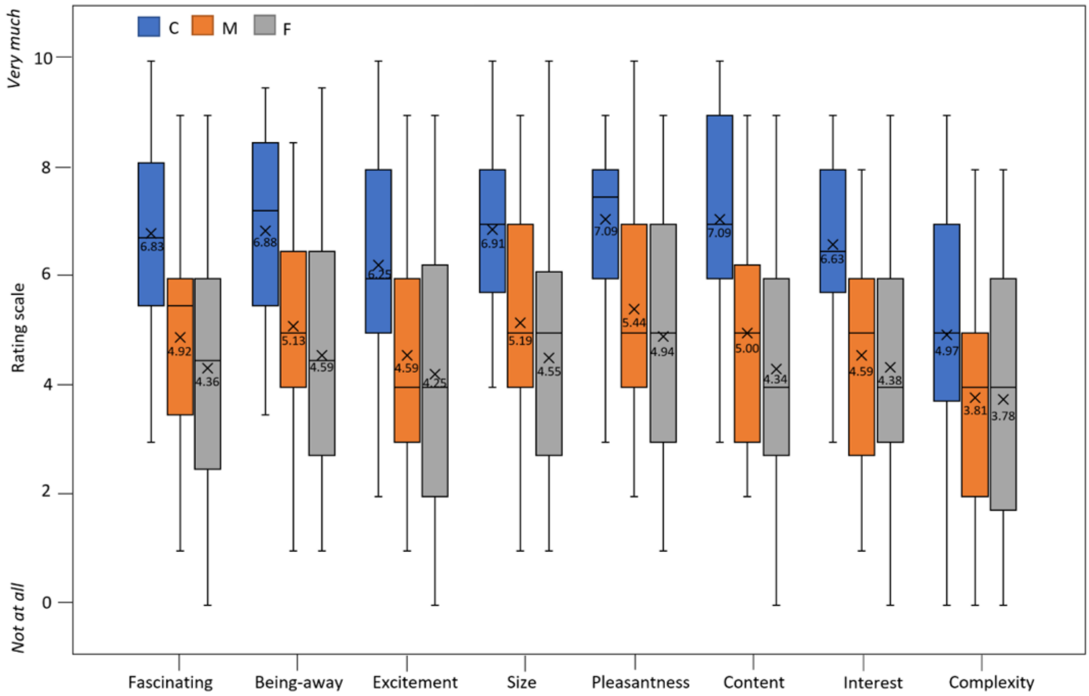

Figure A2-6. Boxplots of view perception parameters at each test session (variation of observing location). Note: the crosses indicate the mean of the group condition.

The repeated-measures ANOVA test was used to compare the mean average evaluations given to the right parameters of view perception across the three observing locations. Table A2-3 reports the F test statistic and the degrees of freedom (df), the statistical significance (*p*-value), and the effect size (η_p^2). The results from the ANOVA indicate significant differences for all eight parameters across the three viewing locations.

Table A2-3. ANOVA and effect sizes for each questionnaire item on view perception

Parameter	*F* (*df*= 2)	*p*-value	Effect size (η_p^2)
Fascinating	25.06	0.00***	0.45
Being away	22.09	0.00***	0.42
Excitement	19.53	0.00***	0.39
Size	16.18	0.00***	0.38
Pleasantness	19.98	0.00***	0.39
Content	24.76	0.00***	0.44
Interest	22.66	0.00***	0.42
Complexity	5.82	0.02**	0.16

* weakly significant; ** significant; *** highly significant; n.s. not significant
η_p^2<0.04= negligible; η_p^2≥0.04= small; η_p^2≥0.25= moderate; η_p^2≥0.64= large

Substantial effects were detected ($0.25<\eta_p^2\leq0.64$), except for complexity which had a significant difference at ($p<0.05$) with small detected effect. The analysis of the data suggests that for these parameters, the distance from the window has a substantial influence on view perception. When the participant viewed the window view from a closer location, they gave higher ratings to the eight parameters. To isolate the relevant differences in the analyses found in Table A2-3, pairwise comparisons were performed using the dependent *t*-test with Bonferroni adjustment for *p*-value (*p* is significant at 0.05 divided by the number of paired comparisons) to control type I error of rejecting the null hypothesis when it is true [94]. Hence, adjusted significant threshold of *p*-value (0.05/3=0.016) will be used to identify the significant criterion.

Table A2-4. Pairwise comparisons between test sessions and effect sizes for each parameter

Parameter	Sessions	$Mean_1$ (SD)	$Mean_2$ (SD)	ΔMean	*p*-value	Effect size (r)
Fascinating	C vs. M	6.83 (1.87)	4.92 (1.89)	1.91	0.00***	0.69
	C vs. F	6.83 (1.87)	4.36 (2.31)	2.47	0.00***	0.79
	M vs. F	4.92 (1.89)	4.36 (2.31)	0.56	0.16 n.s.	0.25
Being away	C vs. M	6.88 (1.84)	5.13 (1.82)	1.75	0.00***	0.69
	C vs. F	6.88 (1.84)	4.59 (2.30)	2.28	0.00***	0.73
	M vs. F	5.13 (1.82)	4.59 (2.30)	0.531	0.16 n.s.	0.25
Excitement	C vs. M	6.25 (2.10)	4.59 (2.06)	1.66	0.00***	0.66
	C vs. F	6.25 (2.10)	4.25 (2.55)	2.00	0.00***	0.73
	M vs. F	4.59 (2.06)	4.25 (2.55)	0.34	0.34 n.s.	0.17
Size	C vs. M	6.90 (1.65)	5.19 (2.12)	1.72	0.00***	0.62
	C vs. F	6.90 (1.65)	4.55 (2.46)	2.36	0.00***	0.66
	M vs. F	5.19 (2.12)	4.55 (2.46)	0.64	0.13 n.s.	0.27
Pleasantness	C vs. M	7.09 (1.53)	5.44 (1.98)	1.66	0.00***	0.67
	C vs. F	7.09 (1.53)	4.94 (2.26)	2.16	0.00***	0.73
	M vs. F	5.44 (1.98)	4.94 (2.26)	0.50	0.20 n.s.	0.23
Content	C vs. M	7.09 (1.79)	5.00 (2.16)	2.09	0.00***	0.69
	C vs. F	7.09 (1.79)	4.34 (2.38)	2.75	0.00***	0.76
	M vs. F	5.00 (2.16)	4.34 (2.38)	0.66	0.11 n.s.	0.28
Interest	C vs. M	6.63 (1.74)	4.59 (2.10)	2.03	0.00***	0.71
	C vs. F	6.63 (1.74)	4.38 (2.34)	2.25	0.00***	0.68
	M vs. F	4.59 (2.10)	4.38 (2.34)	0.22	0.48 n.s	0.13
Complexity	C vs. M	4.97 (2.43)	3.81 (2.09)	1.16	0.01**	0.52
	C vs. F	4.97 (2.43)	3.78 (2.42)	1.19	0.05 n.s.	0.41
	M vs. F	3.81 (2.09)	3.78 (2.42)	0.03	0.93 n.s	0.02

Bonferroni corrected: * weakly significant; ** significant; *** highly significant; n.s. not significant
r<0.20 = negligible; 0.20≤r<0.50 = small; 0.50≤r<0.80 = moderate; r≥0.80 = large

Table A2-4 presents the results of the pairwise comparisons for each questionnaire parameter, providing the mean and the standard deviation (SD) for the rating scores calculated at all test sessions, the difference between the means (ΔMean), the *p*-values, and the effect size (*r*). The pairwise comparisons provide evidence that the differences between subjective rating scores, reported at different observing locations within the room, were highly significant in 15 cases, not significant in nine cases, out of a total of 24 comparisons. The differences have “moderate” effect sizes in 15 cases, “small” in six cases, and “negligible” in three cases.

For nearly all parameters, highly significant differences and the largest effect sizes were detected when comparisons were made with both the middle and far viewing locations against the close condition, except for complexity between C and F. This generally shows that there were significant decreases in the evaluations given for all parameters measured when participants were positioned further away from the window in the VR setting. Interestingly, comparisons made between the viewing positions M and F showed no statistically significant differences. The size of the differences ranged from “small” and “negligible”, which suggests that participants have similarly perceived the views in these two conditions.

Figure A2-7 indicates the change in mean ratings on the valance/arousal Circumplex model of affects. The locations of mean rating demonstrate the change in perceived affects corresponding to each viewing location. When participants were closer to the window in the virtual environment, they reported more pleasantness and arousal compared to middle and far locations – with "moderate” differences as shown in Table A2-4. The location of the close position suggests that there was a stimulating affect. However, the mean ratings of view perception given to the middle and far locations in terms of arousal/valance shifted towards the dull criterion, which is associated with lower arousal and pleasantness resulting in a less stimulating working environment.

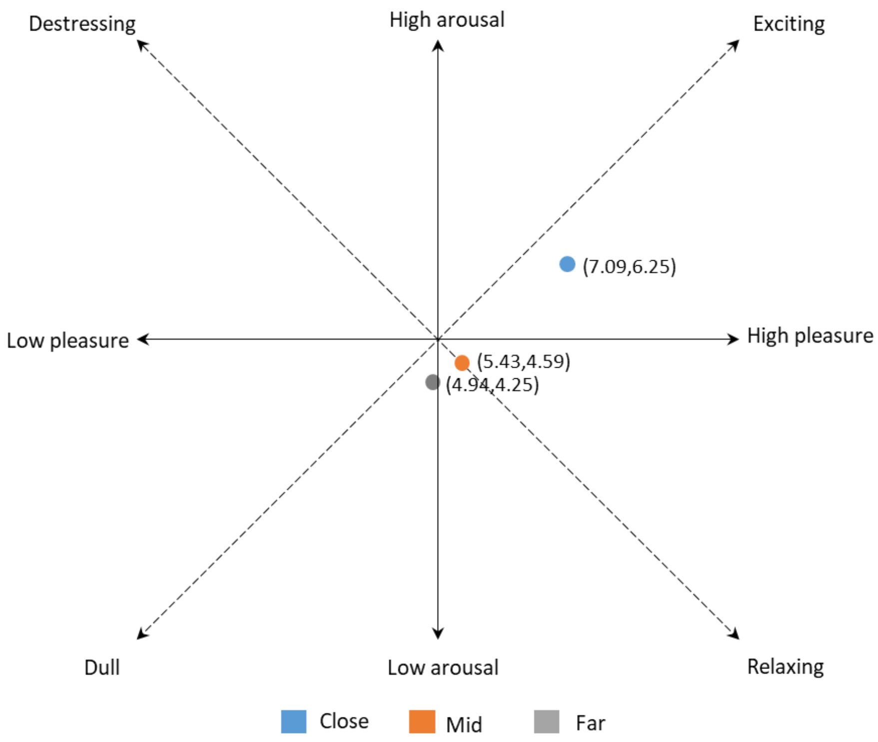

Figure A2-7. Locations of mean ratings of view perceived valance/arousal on the Circumplex model of affects adopted from [43]

A2.3.2 Self-Reported Stress and PANAS

The results of the Friedman's ANOVA showed that there was a significant difference in the change in positive affects (ΔPA) when compared to the baseline PA across the three viewing locations: $\chi^2(2)= 8.93$, $p\leq0.01$**. The differences in self-reported stress (ΔStress) and negative affects revealed no significant differences and no follow-up analyses were performed. These results suggested that subjective recovery was almost equal at all three locations from the window, except for ΔPA. Pairwise comparisons using Wilcoxon signed-rank test were conducted to explore the magnitude of differences in ΔPA across the three different locations.

Table A2-5. Wilcoxon signed-rank tests and effect sizes for subjective recovery parameters

Parameter	Conditions	M_{1dn} (IQR)	M_{2dn} (IQR)	*p*-value	Negative	Positive	Ties	Effect size *r*
ΔPA	C vs. M	-0.38 (5.25)	-1.00 (4.38)	0.02*	7	18	7	-0.28
	C vs. F	-0.38 (5.25)	-1.50 (3.75)	0.06 n.s.	5	18	9	-0.23
	M vs. F	-1.00 (4.38)	-1.50 (3.75)	0.76 n.s.	11	11	10	-0.04

Bonferroni corrected: * weakly significant; ** significant; *** highly significant; n.s. not significant
$r<0.20$ = negligible; $0.20 \leq r<0.50$ = small; $0.50 \leq r<0.80$ = moderate; $r \geq 0.80$ = large

The Wilcoxon signed-rank tests (Table A2-5) indicate that the differences between subjective recovery parameters reported at different observing distances from the window were significant when comparing the viewing location C to M. The results showed lower ΔPA at the close location, indicating better stress recovery for this parameter. The decrease in reported PA was smaller at the C location compared to M and F, with negligible difference between the latter as indicated by the median values and large numbers of positive ranks. ΔPA was reported lower at the three conditions compared to the baseline as indicated by the median values; hence, was not able to retain the original state of positive affects before stress induction.

A2.3.3 Physiological Data

Enhanced non-significant recovery trend in HRV (LF-HRV, HF-HRV, and LF/HF) as participants become closer to the window was detected. However, the initial inferential results when comparing the differences in the initial response and stress-recovery data when participants first observed the view using SCR, HR, LF-HRV, HF-HRV, and LF /HF were not statistically significant and have not been evaluated in further analyses.

Figure A2-8 presents the results of SCL during stress induction and recovery. The y-axis shows SCL, and the stress and recovery periods are displayed on the x-axis for when the physiological measurements were collected at different observing locations: C, M, and F. The boxplots in Figure A2-8 suggest a tendency for statistical parameters (mean, minimum, 25th percentile, median, 75th percentile, and maximum) to correspond to lower SCL values when participants are closer to the window during task performance and recovery.

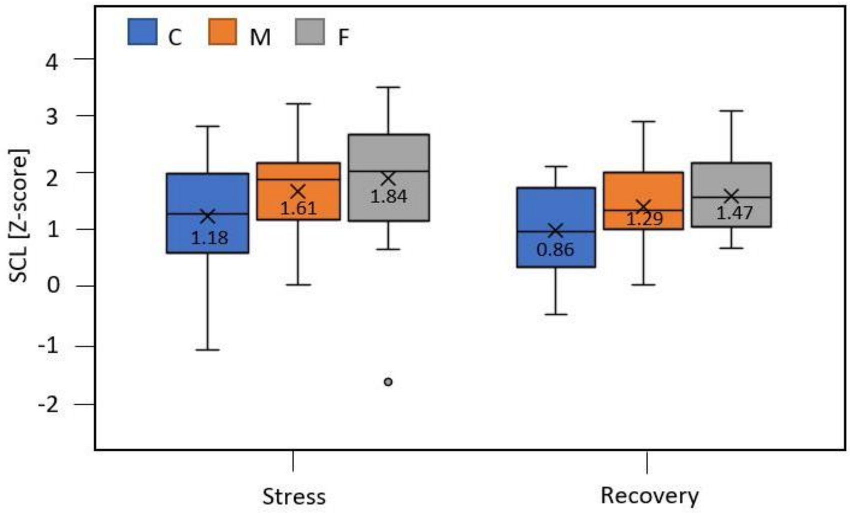

Figure A2-8. Boxplots of SCL during stress and recovery at different viewing positions

ANOVA tests were used to compare the SCL score for the three observing locations. The results from the ANOVA indicate a significant difference in SCL during task performance and recovery. SCL data showed weakly significant values $F(2,54)=4.01$, $p<0.05$ among the three conditions with small effect detected ($0.04<\eta_p^2\leq0.25$) during the task performance; whereas for recovery, SCL showed highly significant difference $F(2,54)=8.26$, $p<0.001$ among the three conditions with small effect detected ($0.04< \eta_p^2\leq0.25$).

Pairwise comparisons were used to identify which observing location has affected the SCL. Table A2-6 shows the results of the pairwise comparisons for SCL during stress induction (i.e., task performance) and recovery, providing the mean (M) and the standard deviation (SD) for the rating scores calculated at all test sessions, the difference between the means (ΔMean), the statistical significance (*p*-value), and the effect size *r*.

Table A2-6. Pairwise comparisons between test sessions and effect sizes for each parameter

Parameter	Sessions	M_1 (SD)	M_2 (SD)	ΔMean	*p*-value	Effect size *r*
Task SCL	C vs. M	1.18 (1.01)	1.61 (0.84)	-0.44	0.04 n.s.	0.39
	C vs. F	1.18 (1.01)	1.84 (1.11)	-0.66	0.02 n.s.	0.44
	M vs. F	1.61 (0.84)	1.84 (1.11)	-0.22	0.36 n.s.	0.18
Recovery SCL	C vs. M	0.86 (0.77)	1.29 (0.70)	-0.43	0.01*	0.48
	C vs. F	0.86 (0.77)	1.47 (0.62)	-0.61	0.00***	0.62
	M vs. F	1.29 (0.70)	1.47 (0.62)	-0.18	0.27 n.s.	0.20

Bonferonni corrected: * weakly significant; ** significant; *** highly significant; n.s. not significant
$r<0.20$ = negligible; $0.20\leq r<0.50$ = small; $0.50\leq r<0.80$ = moderate; $r\geq0.80$ = large

The pairwise comparisons provide evidence that the differences between SCL data were not significant in all three comparisons. The differences have “small” magnitudes ($0.20\leq r<0.50$) in two cases and “negligible” ($r<0.20$) in one out of three cases. The differences examined for the SCL data were highly significant in one case, significant in one case, and not significant in one out of three cases. The effect size has a substantive magnitude and was “moderate” in one case ($0.50\leq r<0.80$) and “small” ($0.20\leq r<0.50$) in two out of three comparisons.

The analysis of the data suggests that the view perceived at different viewing locations from the window may have a direct influence on the stress levels during task viewing and recovery. The differences were largest when the difference in viewing location varied the most (C vs. F). But the differences in task viewing and recovery were still practically significant for comparisons made between viewing locations C vs. M. Interestingly, comparisons between M vs. F were not significant and had "negligible" effect sizes. This result is consistent with the findings derived from the subjective evaluations reported in Table A2-4, whereby no convincing evidence of the viewing location across these same two conditions was found. This suggests that after a certain distance from the window, the view quality will be similarly perceived.

A2.3.4 Reported Simulator Sickness Symptoms

SSQ questionnaires before and after using the experiment were collected using ordinal scale and analysed using the Wilcoxon signed-rank test. The following symptoms were significantly different before and after using the VR: 'Fatigue', 'Eye Strain', 'Difficulty concentrating', 'Fullness of the Head', and 'Blurred Vision' all with small effect sizes, except for eye strain which showed a moderate effect size. The other symptoms: 'General Discomfort', 'Headache', 'Difficulty Focusing', 'Salvation Increasing', 'Sweating', 'Nausea', 'Dizziness', 'Eyes Open', 'Dizziness Eyes Closed', 'Vertigo', 'Stomach Awareness', and 'Burping' were not significantly different (p>0.05) with small or negligible effect sizes. The significant results are indicated in Table A2-7.

Table A2-7. Results of the Wilcoxon signed-rank tests for responses to questions on simulator sickness questionnaire

Parameter	After (M_{dn})	Before (M_{dn})	p-value	Negative	Positive	Ties	Effect size r
Fatigue	1	1	0.01*	10	1	21	-0.34
Eyestrain	2	1	0.00***	19	0	13	-0.55
Difficulty Concentrating	1	1	0.03*	7	1	24	-0.27
Fullness of the Head	1	1	0.04*	9	2	21	-0.26
Blurred Vision	1	1	0.02*	8	1	23	-0.29

* weakly significant; ** significant; *** highly significant; n.s. not significant
r<0.20 = negligible; 0.20≤r<0.50 = small; 0.50≤r<0.80 = moderate; r≥0.80 = large

Table A2-7 indicates that significantly reported symptoms were denoted by small effect sizes and a high number of ties (tied ranks >19) for all symptoms (i.e., when the evaluations across both conditions were the same), except for reported levels of eye strain. However, as found in the first experiment, all participants before leaving the experiment setting have reported that any discomfort that was experienced during the VR trial has subdued.

A2.4 Discussion

The results of this study show substantially difference in the subjective and physiological measures given to perceived view quality at different locations in a virtual environment replicating a daylit office room.

The findings in this study showed that when participants observed the view at the close position in the VR setting, higher positive affects were reported (Table A2-5), and lower stress levels were observed from physiological measurements of skin conductance (Table A2-6). These same restorative benefits were not found when participants observed the window view in the VR setting from further distances. These findings may be linked to the attention restoration [34] and the affective response [35] theories, whereby stimuli that are perceived positively (e.g., visual information from a window view) induce positive cognitive and physiological reactions (e.g., reduced levels of negative emotions and reductions in physiological stress). At the close position from the window view, the visual information perceived by the participants diverted their attention away from the stressor (i.e. the Stroop test) and decreased the levels of psychological and physiological stress. At further distances in the VR setting, this process may have been less apparent and accordingly, the beneficial responses measured also decreased.

All subjective parameters used to evaluate view perception (i.e., view restorative ability, view content and size, view valance/arousal, interest and complexity) were significantly higher for the close condition compared to middle and far conditions. View perception parameters were not significantly different between middle and far conditions. These differences suggest that participants did not perceive any difference between the two viewing positions, which was also detected in the physiological data (Table A2-6). The main change between view content across the viewing locations was the sky component of the view, whereby this was only visible from the closest position. Literature has emphasised the importance of being able to see the sky within the window view [96], which may provide occupants with valuable information regarding the weather and time of day that they might have limited access to when inside the building.

At a certain viewing distance away from the window, observer location does not matter, and the window view is similarly perceived. This might be due to the sky is being no longer visible as seen in Figure A2-2 from the middle position. Therefore, the design of windows in offices should take into consideration the role of the sky component to promote a higher quality view.

In general, the subjective assessment of the view perception indicated that increasing the distance from the window results in a lower preference of view perception to a wide range of parameters. Observers' satisfaction with view size was rated moderately higher for the close condition compared to middle and far conditions. This supports that satisfaction with view size should be assessed in terms of view size in the visual field instead of the WWR. On the Circumplex model of affects (Figure A2-7), the change in valance/arousal across the three viewing positions in the VR setting also resulted in notable changes in the mean values of affect along with the excitement–dull axis. This also supported the idea that less stimulating working environments are created when occupants are further away from the window view [44].

Subjective recovery from the stress (ΔPA) showed improved values when participants were located closer to the window in the virtual environment (Table A2-5). Similar values of PA to those recorded prior to being exposed to the stressor (Stroop test) were found when participants viewed the view from the close position (i.e., indicating lower levels of stress when they were positioned closer to the window). On the other hand, objective stress recovery using SCLs was substantially lower when measured at the close position, and slightly lower between the middle when compared to the far viewing condition (Table A2-6). This finding indicates that more restorativeness of the view occurred at the close location and supports other derived results. The subjective and objective findings could help explain why occupants generally prefer to sit closer to the window (i.e., attaining its restorative benefits) [11, 30, 31].

In BREEAM recommendations, a 20% WWR for rooms with depth ≤8 m is recommended for view, and all occupants are to be within 8 m from the window which consists of landscape or buildings not only sky, or to be an internal view as long as it is 10 m away from the window to allow visual relief for the eye by refocussing on distant content. In this study, a window view with a façade WWR of 20% that was viewed from approximate two metres away from the window (i.e., the middle position) considerably reduced the physiological restorativeness effects experienced by the observer. Therefore, what would be considered an adequate view can maintain its quality only up to a small distance from the window. This might impose limitations on room depth concerning WWR to attain the view benefits in a deep plan or large open-plan offices, and also highlight the restorative value of the informative elements of the view in an urban context (sky and ground). This study also suggests that views of buildings (i.e., neighbouring building or internal views) might not guarantee an adequate view as shown by mean ratings that shifted from the positive to the negative part of the rating scale as the participants are placed further from the window and the view becomes limited to buildings.

Because window proximity not only influenced subjective evaluations, further work may be needed to evaluate different numbers and shapes of windows, which control the amount of visual information that can be seen by the building occupant. This would, in turn, vary the amount of restorativeness in deep parts of the offices that is needed to satisfy more occupants. The results of these studies can be used to understand how physiological parameters measured from the participants translate onto the health and well-being of building occupants.

Although VR can produce realistic visual environments [59] and offer a high degree of control that is difficult to achieve in daylit environments [24], they produce a relatively limited range of luminances due to the current constraints of the technology. While measures were put into place to minimise high luminances from being present in the real environment (e.g., using a north-orientated window and a room without direct sunlight), it may not be possible to accurately evaluate the influence of glare or high brightness contrasts in VR settings.

This study also only considered one window view to evaluate the effect of viewing location, which was selected based on experimentation considerations (i.e., its orientation, three layers, etc.). However, the view utilised in this study may not be representative of typical scenarios due to the unique architecture of the neighbouring building seen in the landscape. Therefore, further work may be needed to understand how other views with a wider range of visual characteristics may have influenced the outcome.

Another limitation of this study is the unwanted simulator symptoms that were reported by the participants following the use of VR technology. Although these symptoms have been associated with the application of VR environments [61], they are generally minor and short-lived [110], which is consistent with our findings.

A2.5 Conclusion

In this study, a novel comprehensive method to assess view perception was developed. A 360^{o} virtual environments were used to represent three different viewing positions showing their corresponding window views seen in a daylit office. Several subjective and physiological measures were used to quantify the differences in view perception based on parameters of restorativeness from stress. These differences were evaluated across the different viewing positions. The designed methodology identified statistically significant differences in view perception in the measures that were evaluated. The main findings of this study are:

- The viewing location of the participant from the window has a significant influence on view quality measured through the use of subjective and physiological parameters, whereby decreased view quality was reported the further away the participant was located from the window within the virtual environment.
- Increased view quality was found when participants were closer to the window in the VR setting. When comparing the differences in subjective evaluations given

between the far and close viewing positions: the self-reported levels of “fascination” and “being away” increased by 36 % and 33 %; “excitement” and “pleasantness” increased by 32 % and 30 %; and satisfaction with “view content”, “size”, and perceived “interest” and “complexity” increased by 39 %, 34 %, 34 % and 24 %, respectively.

- Decreases in physiological stress levels were found when participants were closer to the window in the VR setting. Stress levels during recovery showed a 71 % reduction in skin conductance when comparing the measurements collected at the far and close positions.
- At a distance of 2.18 m from the window, no significant changes in view quality were reported between different viewing locations in the VR setting – for both the subjective and physiological parameters. It is postulated that this may be due to the fact that at a certain distance from the window, the sky is no longer visible and participants perceive the view in the same way.
- The recommended use of a 20% WWR given by standards might not guarantee the view benefits (restorativeness) across the room. Alternatively, the windows’ solid angle, position, and other physical dimensions in relation to the view content should be considered.

Cognitive performance was not tested in this study due to the limited resolution of the current VR headset. Future studies could account for this by using non-visual stress induction tasks to assess viewing position impact on cognitive performance. Moreover, different levels of content such as naturalness and moving elements should be studied. Other window design factors impact on view quality perception such as window shape, location, window size, and smart windows applications could be assessed using a similar methodology. Additionally, their corresponding lighting and energy performance could be evaluated using multi-disciplinary research to provide a deeper and complete understanding of windows performance.

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Declaration of Interest

None.

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Appendix A2-1

Table A2-1.1 Experiment detailed procedure and duration

Time progress in minutes	Activity	Duration in minutes
0-10	Welcome and introduction, sign the consent form and complete the Pre-test participant questionnaires (demographic and SSQ).	10
10-15	Demonstration of the experiment in the test room to make sure subjects understand the procedures and familiarize with VR.	5
15-17	Connect SC and HR sensors to non-dominant hand and start physiological recordings	2
17-19	Participants wear VR /start baseline physiological measurement	2
19-24	Participants complete the questionnaire (stress and PANAS)	5

24-34	View the first condition for one minute, and answer view perception questionnaire, complete Stroop test, and then look at window view to recover.	10
34-36	Participants complete the questionnaire (stress and PANAS)	2
36-43	Participants rest outside the experiment room and experimenter prepare for second condition	7
43-47	Take baseline measurements	4
47-57	View the second condition for one minute, and answer view perception questionnaire, complete Stroop test, and then look at window view to recover	10
57-59	Participants complete the questionnaire (stress and PANAS)	2
59-66	Participants rest outside the experiment room and experimenter prepare for next condition	7
66-70	Take baseline measurements	4
70-80	View the third condition for one minute, and answer view perception questionnaire, complete Stroop test, and then look at window view to recover.	10
80-82	Participants complete the questionnaire (stress and PANAS)	2
82-87	The participants sign post-study consent form and SSQ questionnaire	5
87-90	End of experiment. The participant will be thanked for their time, led to the door and told they are free to leave	3

Appendix A2-2

Evaluating the Impact of Viewing Location on View Perception Using a Virtual Environment

Participant Information Sheet

Project Title: Evaluating Visual Performance in Virtual Office Space Using Physiological Measures

Researcher: Fedaa Abd-Alhamid [laxfa10@nottingham.ac.uk]

Supervisor(s): Dr. Yupeng Wu [Yueng.Wu@nottingham.ac.uk], Dr. John Calautit, and Dr. Peter Rutherford

Advisor: DR. Michael Kent

Thank you for agreeing to take part in this research study about evaluating visual performance in virtual office environment. Before you begin, we would like you to understand why the research is being done and what it involves for you.

The Study

The purpose of this study is to evaluate the effectiveness of virtual reality in assessing visual performance. During the test, some of your physiological signals (e.g., heart rate and skin conductance) will be monitored. You have been invited because you meet the criteria the research required:

i. Between the age of 18 and 45.
ii. Speak fluent English.
iii. Willing to view a virtual reality environment using head mounted display.
iv. Who do not have any neurological disorders (e.g., epilepsy).
v. Who do not suffer from migraines, motion sickness, dizziness or sleep disorders.
vi. Who are not visually impaired (e.g., glaucoma).
vii. Who do not have colour vision defects (e.g., colour blindness).
viii. Willing not to overwork or intake caffeine for the 8 hours prior to the study.
ix. Willing not to intake alcohol for the 24 hours prior to the study.

We would like to remind you that this study is optional, and it is up to you to decide whether to take part. If you do decide to take part, you will be asked to sign a consent form. Following this, you will be asked to fill out an initial questionnaire to collect some basic information about yourself including demographic information (age, gender etc.) and simulator sickness questionnaire.

Afterward, the researcher will then lead you into a test room where heart rate sensor will be connected to your middle finger and two skin conductance sensors will be connected to your index and ring fingers. All sensors will be connected to your left hand. The recorded signals will be sent to a computer to record the results. This procedure is widely accepted to have no risk and to be a non-invasive technique to record physiological response.

Then you will be exposed to three different virtual environments and asked to complete a simple task during each. This will include stating the colours of words on a task on the wall. After each test environment you will be asked to fill out a questionnaire followed by a seven-minute break before taking the next test environment.

Will the research be of any personal benefit to me?

You are voluntarily participating in this study. We cannot promise the study will help you personally, but the information we get from this study may help gain a better insight into better architectural space requirements for decreased stress levels within office environments.

Are there any possible disadvantages or risks in taking part?

When using virtual reality, there is a risk that you might experience "simulator sickness". It involves symptoms similar to those of motion-induced sickness, although simulator sickness tends to be less severe and to be of lower incidence. People who suffer from epilepsy, migraines, motion sickness, dizziness, sleep disorders or blurred vision are more likely to experience adverse effects, so please do not take part in the study if you suffer from any of these conditions. If you experience any symptoms during the session, or any other discomfort, please alert the investigator immediately, or you can simply remove the headset yourself, like you would a pair of googles.

What will happen to the information I provide?

We will follow ethical and legal practice and all information will be handled in confidence. The data collected for the study will be looked at and stored by authorised persons from the University of Nottingham who are organising the research. They may also be looked at by authorised people from regulatory organisations to check that the study is being carried out correctly.

What if there is a problem?

If you have any queries or complaints, please contact the student's supervisor/ investigator in the first instance.

What if I have other questions?

If you have any questions or concerns, please do not hesitate to ask. The researchers can be contacted before and after your participation at the email addresses above.

Participant Consent Form

Project Title: Evaluating Visual Performance in Virtual Office Space Using Physiological Measures

Researcher: Fedaa Abd-Alhamid [laxfa10@nottingham.ac.uk]

Supervisor(s): Dr. Yupeng Wu [Yueng.Wu@nottingham.ac.uk], Dr. John Calautit, and Dr. Peter Rutherford

Advisor: DR. Michael Kent

I the undersigned as research participant confirmed that (please sign your initials as appropriate)

- ☐ 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 do not suffer from any of the following: epilepsy, migraines, motion sickness, dizziness, sleep disorders or blurred vision.
- ☐ 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, and that digital data will be stored only on a password-protected computer and on a secure server. Only researcher 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 supervisor and the supervisor 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 ……………………………...… Date …………………………………

Signed ………………………………………………………… (Researcher)

Print name ……………………………….…… Date ………………………………….

Post Study Participant Consent Form

Project Title: Evaluating Visual Performance in Virtual Office Space Using Physiological Measures

Researcher: Fedaa Abd-Alhamid [laxfa10@nottingham.ac.uk]

Supervisor(s): Dr. Yupeng Wu [Yueng.Wu@nottingham.ac.uk], Dr. John Calautit, and Dr. Peter Rutherford

Advisor: DR. Michael Kent

I the undersigned as research participant confirmed that (please sign your initials as appropriate)

- ☐ Any feelings of discomfort I may have felt during the trials have subsided.
- ☐ I have been advised to wait for approximately 30 minutes between completing the simulator trial and driving

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

Print name ……………………………...… Date …………………………………

Signed ………………………………………………………… (Researcher)

Print name ………………………….…… Date ………………………………….

Contact details:

Researcher: Fedaa Abd-Alhamid [laxfa10@nottingham.ac.uk]

Supervisor: Dr. Yupeng Wu [Yueng.Wu@nottingham.ac.uk]

Pre-Test Subject Questionnaire

Participant Number ______

Time________________

Date_________________

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

What is your gender? □Male □Female

1. What is your age? ____

2. What is your academic background? (e.g. Engineering/Social Science, UG/PhD/research fellow, etc.) ______________________________________

3. Do you have any problems with your vision?

□Colour blindness □ Colour weakness □ Short sightedness □Far sightedness □None □Others_________________

4. If yes, are you using glasses or contact lenses to correct any eye conditions?

□ Yes □ No

5. What is your ethnic background?

□ White □ Mixed / Multiple ethnic groups □ Asian

□ Black / African / Caribbean / Black British □ Other ethnic group ______

6. What is current state of health? □ Ill □ Not too bad □Good

7. 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.

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Appendix A3

Paper 3: A Holistic Approach to Assess Window Performance: Optimizing Window Size for View Perception, Energy, and Daylight

(This part is written in a paper format to be submitted for journal publication)

A Holistic Approach to Assess Window Performance: Optimizing Window Size for View Perception, Energy, and Daylight

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Abstract

An efficient design of windows in built environments should consider its energy and daylight performance, and the connection to the outdoors provided by the views from the windows. The latter is insufficiently studied despite being a critical factor contributing to occupants' wellbeing and satisfaction with the indoor environment. While window size optimization has been investigated for daylight and energy, its impact on view perception has not been comprehensively investigated. In this study, view perception was evaluated using a physically-based 360º virtual environment with five different window sizes: 30%, wide 20%, narrow 20%, wide 10%, and narrow 10%, presented to twenty-five participants. The study employed a comprehensive evaluating method by collecting subjective and physiological evaluations. Subjective assessments included questions on view restorative ability, view content and size preferences, view valance/arousal, besides stress, positive and negative affects. Physiological measures included skin conductance, heart rate, and heart rate variability. Results showed significant differences in subjective parameters and measures of skin conductance and heart rate variability. Decreased view quality was reported as participants observed the view from smaller window sizes compared to the 30% case. The view quality from different window sizes was assessed against the corresponding energy and daylight performance to provide a holistic assessment to assess window performance. The study highlights the importance of considering the view quality when optimizing window design as the optimizing window size for energy and daylight alone might not guarantee view restorativeness for building occupants, and ultimately affecting their health and well-being.

Keywords: Visual comfort; View perception; Virtual Reality (VR); Window performance; Daylight performance; Energy consumption.

A3.1 Introduction

Windows are an important feature in the design of any building; their role in visual comfort and corresponding energy consumption has been investigated and various window designs have also been examined to optimize windows performance (e.g., window to wall ratio (WWR) and smart window systems). The optimization is usually performed to minimise the energy consumption and to maximise the daylight access within the building [1-3].

Heating, cooling, ventilation, and artificial lighting energy consumption are usually considered for windows optimization [1, 3, 4]; whereas for daylight, windows optimization is often performed based on indoor illuminance levels using several indicators such as Daylight Factor (DF), Daylight Autonomy (DA), Useful Daylight Illuminance (UDI) [5], uniformity, and glare [6,7].

Significant studies have been conducted to investigate the impact of WWR, defined as net glazing area/ total wall area where the window is located [2], on building energy consumption and daylight performance independently or simultaneously. Some representative studies have recommended different optimized WWR based on the simulated climate and the office orientation as indicated in Table A3-1.

Table A3-1. Summary of studies on WWR optimization with used criteria

Glazing type	Room dimension (m)	Region	Climate*	WWR	Orientation	Optimization criteria	Ref.
Double glazed	-	Wuhan (China)	Cfa	0.10	E, W, S, N	Energy consumption	[1]
Double glazed	5.0x6.0x3.0	Harbin Beijing Hangzhou Kunming Guangzhou (China)	Dwa Dwa Cfa Cwb Cfa	0.20 0.20 0.30 0.20 0.40	S	Energy consumption and useful daylight illuminance UDI using (<500, 500-2000, and>2000 lux) for insufficient, sufficient, and glare respectively	[2]
Double and triple glazed	6.1x4.6x3.1	Manila (Philippines)	Af	0.25 0.50	E, S, W N	Energy consumption	[3]
		Taipei (Taiwan)	Cfa	0.25 0.50	E, S, W N		
		Shanghai (China)	Cfa	0.25 0.50	E, S, W N		
		Seoul, (South Korea)	Dfa	0.25 0.50	E, S, W, N		
		Sapporo, (Japan)	Dfa	0.25	E, W, S, N		
Double glazed	3.0x6.0x3.0	UK	Cfb	0.20-0.40	E, W, N	DA using 250 and 2500 lux for minimum and maximum thresholds	[6]
				0.10-0.30	S		

low-e coated triple glazed with argon in the cavities	3.7x5.4x3.2	Oslo (Norway)	Dfb	0.37-0.43	E, W, N	Energy consumption, DA using 500 lux for sufficient lighting and UDI for glare risk (>2000)	[4]
				0.50-0.60	S		
		Frankfurt (Germany)	Cfb	0.37-0.45	E, W, S		
				0.40-.045	N		
		Rome (Italy)	Csa	0.30-0.35	E, W		
				0.25-0.35	S		
				0.35-0.40	N		
		Athens (Greece)	Csa	0.30-0.35	E, W		
				0.35-0.40	S, N		
Double glazed	3.5x5.3x2.7	Amsterdam (Netherlands)	Cfb	0.50-0.70	N	Energy consumption, and a minimum of 500 lux for sufficient lighting, uniformity ≤ 3.5, and Below 22 Hours of glare using Daylight Glare Index (DGI)	[7]
				0.50-0.60	E, W		
				0.60	S		

*Climate description according to Köppen–Geiger climate classification system [8]
Cfa: Humid subtropical climate
Dwa: Monsoon-influenced hot-summer humid continental climate
Cwb: Subtropical highland climate
Af: Tropical rainforest climate
Dfa: Hot-summer humid continental climate
Cfb: Temperate oceanic climate
Dfb: Warm-summer humid continental climate
Csa: Hot-summer Mediterranean climate

In other window design optimization studies (e.g., shading optimization), the connection to the outdoors provided by the view through shadings is either neglected, or considered by performing calculations for the amount of the available view [9, 10], despite being a critical factor contributing to occupants' wellbeing and satisfaction with the indoor environment [11-15]. However, the amount of provided view through the shading systems might not guarantee an adequate view as view quality is not considered.

One reason for not considering the view perception in similar studies may be the difficulty to conduct view perception experiments in continuously changing daylit environment [16, 17] and the difficulty to change the different window designs alternatives to investigate their impact on view perception (i.e., different WWR, different shading devices, smart windows, etc.). Another reason might be the inadequate methods available to quantify view quality as opposed to the tools available for energy and lighting performance simulation.

While new designs offer freedom to the architects in terms of window-to-wall ratios, orientations, and smart glazing systems, their impact on view perception and the optimal point among view perception, energy, and daylight performance must be considered. Therefore, multi-criteria studies on window performance optimizations are needed in order to identify the minimum acceptable amount of view that guarantee the view quality (i.e., the threshold of reduction in available view that causes a significant difference in view quality perception) to account for when different window optimizing designs are developed.

According to literature, small views provided by windows are the least favoured by buildings' occupants and larger window sizes are preferred [17-19]. For example, people reported relatively large window sizes in different studies (e.g., 35 % [18], 50 [20], 80 % [21], 40 % [17], 100 % [22]). Consequently, smaller windows acceptance and quality of views provided issues might emerge and impose constraints on energy and daylight WWR optimization studies. This might occur under certain climates and orientations as relatively small WWRs were found to be more efficient in terms of energy and daylight performance. For example, for energy performance optimization in all window's orientations, a 10% and 25% WWRs were the optimized size in

Wuhan, China [1] and in Sapporo, Japan [3] respectively. For daylight optimization, WWR range between 10% and 40% was recommended for UK [6]. For energy consumption and daylight availability, WWR range between 20% and 40% was recommended for south oriented windows in different climates regions in China [2], and ranges between 25% and 40% and between 30% and 40% were recommended for Rome, Italy, and Athens, Greece, respectively [4]. Accordingly, the selected WWRs in this study were relatively small ranging between 10% and 30% to find a threshold of acceptance of reduced WWR for view perception; in order to optimize the window size for view perception, daylight, and energy performance. Additionally, different layouts were used for smaller WWR to assess its impact on view perception (i.e., whether the dimensions of the window could affect the occupant's acceptability of smaller WWRs).

To this end, this study aims to develop a comprehensive approach to evaluate the window performance using a threefold criterion to assess window size impact on view perception, energy, and daylight performance. A validated 3-dimensional virtual reality (VR) representation method [23] was used to represent the different experimental conditions. This method provides an immersive VR setting, stereoscopy vision to create depth perception [24], and, within certain degrees, can produce realistic visual contrast and colour properties [23]. VR also offers a much higher degree of experimental control over parameters that would vary in buildings including temperature, noise, and daylight (i.e., CCT, illuminance and luminance levels), which can affect the investigated visual stimuli perception if left uncontrolled [16, 17]. For view perception, WWR was optimized using a method developed in the previous study [25] to quantify view quality based on stress-recovery comprehensive subjective and objective (physiological) evaluations. Optimized WWR for energy and lighting performance was determined via simulations.

Four research objectives were derived: (1) developing a replica in virtual reality of five different window sizes: a 30%, wide 20% (20%W), narrow 20% (20%N), wide 10% (10%W), and narrow 10% (10%N), within a typical office room based on their physical and luminous conditions in a 3-dimensional virtual simulated setting using validated physically-based images technique; (2) collecting subjective responses on view quality parameters including view restorative ability, view content and size preferences, and view valance/arousal, in addition to self-reported stress, positive and negative affects reported throughout the experiment; (3) collecting objective responses (physiological markers) namely skin conductance, heart rate, and heart rate variability to objectively assess the variances in view perception from different window sizes; (4) performing the corresponding energy and daylight performance simulation to the five window sizes to provide the optimized window size considering view perception. This study allows a multi-disciplinary analysis of window design quality and provides a holistic evaluation of windows performance.

A3.1 Methodology

This study was conducted in three stages: (1) collecting subjective and objective (physiological) responses on view quality perceived from different window sizes; (2) modelling a typical office with different window sizes to investigate their energy and daylight performance under three different climates, using EnergyPlus for simulations; (3) evaluating the results obtained in (1) and (2) to determine the optimum window size for view perception, energy and daylight performance.

A3.1.1 Window Size Optimization for View Perception

A3.1.1.1 Experimental Environment

To evaluate view perception from different window sizes, a daylit test room was used to replicate its physical and photometric conditions within a virtual reality environment. The selected room was located on the first floor with a neutral window-view of mixed urban and natural elements that can be found in urban areas [26] and considered as an adequate view by BREEAM guide for green buildings practice [27]. The office room had internal dimensions of 4.35 x 2.85 m and a floor to ceiling height of 3.2 m and had a double-glazed window with 30% window to wall ratio and the window had dimensions of 1.40 m×2.10 m. The internal walls of the room had reflectance (ρ) properties: $\rho_{wall} \approx 0.7$, $\rho_{floor} \approx 0.1$, and $\rho_{ceiling} \approx 0.8$ as estimated using the Munsell values [28].

The room contained standard office furniture and a visual task was mounted 1.50 m from the participant position located at the middle of the room at 2.18 m from the window. View quality perceived through five different window sizes was evaluated: 30%, 20%W, 20%N, 10%W, and 10%N. To mask the different window areas to reduce the window size, an opaque matte white paper with similar reflectance properties to the walls $\rho_{paper} \approx 0.7$ was used to attain the actual daylight distribution from different window sizes when the images are captured for each condition. The final sizes of the windows and their corresponding views are indicated in Figure A3-1.

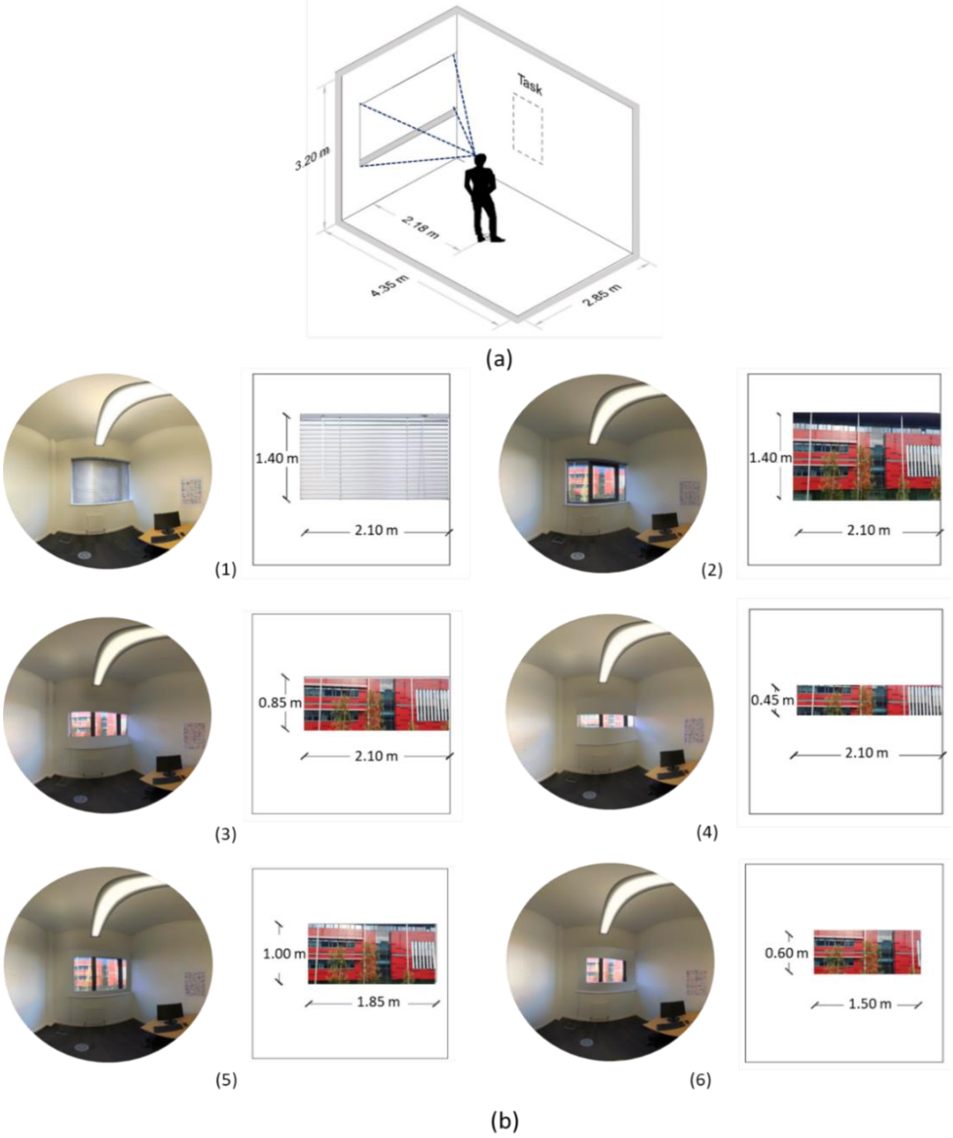

Figure A3-1. (a) The test room dimensions and observer location; (b) the window environment and the corresponding views for 1) the windowless baseline environment; 2) the 30% WWR; 3) the 20%N WWR; 4) the 10%N WWR; 5) the 20%W WWR; 6) the 10%W WWR.

A3.1.1.2 Stress Inducing Task (Stroop Test)

The Stroop test [29, 30] was selected for its ability to elevate stress levels when the task is performed [30-32]. This was needed as the methodology used to quantify view perception is based on stress-recovery as an indicator of view quality [25]. The Stroop test is a colour-word conflict test that often used as a tool for cognitive work assessment, and includes a selective attention feature (i.e., the process by which individuals ignore irrelevant distractions and focus on task-relevant information [33]), which often occurs in office working environments [34, 35].

To counterbalance the possible learning effect, five versions of the test were used for the five different WWRs by randomly allocating the colours and words for each test. Each task consisted of a total of 15 rows with five words on each row, and the text size was 20 mm creating a 0.76° angular size produced by character height, which is within the range needed for fluent reading (between 0.2 to 2°) [36]. Four colours of words: Red, Green, Blue (RGB), representing the three main components of the RGB colour model in lighting studies [37, 38], and black were used for the Stroop test. The selected colours had positions on the chromaticity chart identical to those identified in the previous study [23].

Luminance values of the task were measured using Hagner S3 photometer and compared to those created in the replicated virtual environments. Participants were instructed to name the colours of the words as fast as they can attempting to name even the ones they were uncertain of in 45 seconds [31].

A3.1.1.3 Physically-Based Virtual Environment

In order to replicate the luminous conditions of the test room with different window sizes in the virtual environment, the following equipment were used for photometric measurements: 1) Canon EOS 5D camera equipped with a fish-eye lens (Sigma 4.5 mm f/3.5 EX DG) mounted on a tripod; 2) Minolta Chroma-meter CL-200; 3) Hagner S3 photometer with illuminance sensor; 4) HTC-Vive headset was used to represent the virtual environments. The camera was mounted on a tripod 1.5 m from the wall containing the visual task, 2.18 m from the window and 1.60 m from the floor level to keep the perceived window view in the centre of the participants' field of view. Measurements were repeated five times when different window sizes were applied, corresponding to 30%, 20%W, 20%N, 10%W, and 10%N WWRs.

The validated methodology developed in previous study [23] was used to generate the virtual environments. A total of six 180° HDRI around the room, besides one additional HDRI which was created to mask the tripod area on the floor, were created by combining each image from seven LDRI with different exposures, as indicated in Table A3-2.

Table A3-2. Charge coupled device (CCD) camera settings for each of the seven LDRI

Image	White balance (K)	Sensitivity (ISO)	Exposure time (1/s)	Aperture (f/n)	Exposure Value (EV)
1	4000	100	1/800	4.5	13.97
2			1/250		12.3
3			1/80		10.66
4			1/25		8.98
5			1/8		7.34
6			0.5		5.34
7			1.3		3.95

Six virtual environments were created in this study: one for the windowless neutral baseline conditions and five for window view conditions taken from the participant location. The lowest sensitivity (ISO) 100 was used to reduce the noise in the HDRI. To maintain consistent colour space transitions with fixed white balance (i.e., correct colour temperature (CCT)) [39], a white balance of 4000 K was used, which was the average CCT in the room measured using the Chroma-meter CL-200 (accuracy ± 0.02 %), when the five window sizes were applied at the camera position as indicated in Table A3-3. The HDRI images were calibrated with point luminance measurements and tone-mapped with 2.2 gamma and key value of 0.01 [40] to generate similar contrast values to those found in the real environment.

Table A3-3. CCT measurements to determine white balance used in camera settings

WWR type	10%N	20%N	10%W	20%W	30
Measured CCT	3915	4046	3961	4009	4041
Average	3994.4				

Hanger S3 Photometer was used to measure luminance values of the actual task and the contrast ratios for the Stroop task were obtained using Weber's formula [41], which were calculated using the background luminance of the task and target luminance of the visual characters.

The tone-mapping process was applied to the images projected in the virtual environment to correct the luminance and contrast values, since current virtual head-mounted displays cannot display HDR quality images [23]. Table A3-4 displays the real and virtual contrast values of the Stroop tasks, and the percentages change in contrast between the real and virtual environments across the five conditions.

Table A3-4. Real and virtual luminance and contrast values for different window sizes

Colour		Red	Green	Blue	Black	White (background)	Average Percentage Error (%)
Real environment luminance (cd/m²)	10%N	36	45	38	18	116	
	20%N	44	50	41	19	155	
	10%W	44	47	41	18	147	
	20%W	44	46	37	24	151	
	30%	50	54	41	29	149	
Tone-mapped images relative luminance	10%N	0.32	0.31	0.29	0.13	0.6	
	20%N	0.32	0.3	0.3	0.12	0.6	
	10%W	0.3	0.29	0.2	0.12	0.54	
	20%W	0.28	0.26	0.25	0.1	0.51	
	30%	0.27	0.25	0.25	0.1	0.49	
Real environment Contrast	10%N	-0.7	-0.6	-0.7	-0.8		
	20%N	-0.7	-0.7	-0.7	-0.9		
	10%W	-0.7	-0.68	-0.72	-0.88		
	20%W	-0.71	-0.7	-0.75	-0.84		
	30%	-0.66	-0.64	-0.72	-0.81		
Virtual environment Contrast	10%N	-0.47	-0.48	-0.52	-0.78		0.21
	20%N	-0.47	-0.5	-0.5	-0.8		0.26
	10%W	-0.44	-0.46	-0.48	-0.78		0.30
	20%W	-0.45	-0.49	-0.51	-0.8		0.26
	30%	-0.45	-0.49	-0.49	-0.8		0.23

A3.1.1.4 Physiological Apparatus and Objective Assessment

To evaluate the participants' responses to the views and to evaluate stress levels during the experiment to evaluate the five different window sizes, Skin Conductance (SC), Heart Rate (HR), and Heart Rate Variability (HRV) were measured

Similar experimental set-up utilised in a previous study was adopted [25]. When immersed in the VR setting, participants sat at the centre of the room on a rotatable chair with an armrest that was used to minimise hand-movement when the physiological measurements were recorded. The selected physiological measures can continuously monitor nervous system activity in terms of stress and recovery [42-46]. Both SC and HR data were sampled at 32 samples per second (SPS) rate and were recorded using sensors connected to the Mind Media Nexus-10 MKII acquisition device.

During the experiments, the Ag-AgCL electrodes for the SC sensor were attached to the distal phalanx of the index and ring fingers of the participants' left hand to measure the sweat gland activity of participants regulated by the sympathetic nervous system, indicating states of elevated stress [47, 48]. The HR sensor was connected to the middle finger of the participants' left hand to sense the blood flow rate from which different measures of HRV– including LF-HRV and HF-HRV, and LF/HF ratio– can also be acquired, which expressed in milliseconds squared (ms^2) for a particular Hertz (Hz) band. In this experiment, two more HRV measures were used in the assessment: heart rate variability amplitude (HRV_a) and blood volume pulse amplitude (BVA).

HRV_a indicates the variation in duration between two successive heartbeats where decreased HRV_a is related to mental load while increased HRV_a is related to lower performance anxiety [49, 50]. HRV_a is relatively lower during work periods, thus might be considered as a sensitive indicator of workspaces-stress [50]. On the other hand, BVA refers to the relative changes in the volume of blood in vessels and controlled by SNS and PNS branches of the autonomic nervous system, where increased SNS activity (i.e., stress) contracts the micro-vessels of the finger (i.e., decreasing BVA) while increasing PNS dilates the micro-vessels of the finger (i.e., increasing BVA) [51].

Data at particular points of interest during baseline, stress, and recovery was extracted from continuously recorded physiological responses during each session [48, 52, 53] and the initial responses when participants first observed the window view were also obtained [46, 47, 54]. The SC and HR changes during observing the window view and during recovery from stress were subtracted from baseline measurements in order for the physiological data to be standardised for each participant, to allow the comparison between different experimental manipulations [47]. All physiological recordings were taken while the participants are immersed in the VR.

A3.1.1.5 Physiological Data Screening

To identify the accepted cases for further analysis and to process the physiological data, similar methodology to the one used in previous study [25] was applied and no cases were rejected for SC and HR data. The final sample size for the physiological data analysis was 25 participants, 14 males and 11 females with mean age of 27 years (SD= 5.26).

For the initial response of view observing, SCR data was extracted using a response time of one to 4 s four seconds after presenting the window view with a minimum amplitude of 0.01 μS [47, 48, 52, 55]. HR and HRV data for the initial response to the view was assessed using the mean data for the first 30 seconds after presenting the view. A respective baseline measurement was subtracted using similar response time of SCR and HRV to allow the comparison between experimental conditions [47].

The evaluation of stress and recovery was attained using SCL, HR, and HRV measures. The changes were assessed by using the first minute of recovery from the first minute of exposure to the view to imitate short breaks taken by office workers [25]. This was verified by the participants in this experiment. When were asked about the time they often spend looking at a window view for a short break, 60% of the participants stated that they spend less than two minutes looking for a window view for a short break as shown in Table A3-5.

Table A3-5. The reported time usually spent for short breaks observing views

Viewing time	< 1 min	1 min ≤ and <2 min	2 min ≤ and <3 min	≥3 min	Total
Frequency	5	10	8	2	25
Percent (%)	20	40	32	8	100

Respective baseline measurements (i.e., in the last minute of the baseline) were subtracted from recovery data to attain the change from the baseline [26, 30, 32, 43]. Additionally, the SCL, HR, and HRV during the stress induction (45 seconds of the Stroop test) were compared after being subtracted by the corresponding baseline values to explore stress level during the task performance within the different environments with five different window sizes [26].

A3.1.1.6 Subjective Evaluations

View perception was quantified using a questionnaire on view restorative ability, view content, view size, view valance/arousal, visual interest, and complexity as detailed in the Appendix. All questionnaire items were measured on a continuous scale ranging from “Not at all” (= 0) to “Very much” (= 10) which was explained to participants during the experimental demonstration and reminded with upon making the assessment. Stress levels during the baseline and after the task performance were assessed using self-reported stress question and PANAS questionnaire [56]. Questionnaires were answered verbally and the answers were recorded using Dictaphone, which is more convenient when VR is used [16, 57]. The questions were randomised across the five conditions to eliminate any bias in subjective responses [58]. Reported simulator sickness symptoms produced from immersion in the virtual environment were assessed using the Simulator Sickness Questionnaire (SSQ) [142], which was completed at the beginning and the end of the experiment.

A3.1.1.7 Experimental Procedure

To reduce random variability in the collected data [58], the experiment used a repeated measure design (i.e., the same subject taking part in five conditions). The change in the visual environment due to the window size was the independent variable with five variable conditions: 30%, 20%W, 20%N, 10%W, and 10%N. To counterbalance the effect of presentation order of the stimuli between participants, they were randomly assigned to test order [58].

Questionnaires used in this experiment and the experimental procedure were assessed and approved by the University of Nottingham Ethics Committee. Subjects were either academic staff members or students and were recruited via online advertisements and posters. A total of 25 subjects from different ethnic backgrounds voluntarily participated in the experiment: 14 males and 11 females with mean age of 27 years (SD= 5.26). None of the participants reported any colour vision problems, and 15 participants wore corrective glasses during the experiment.

The study was conducted during winter (January-February) and indoor air temperature and humidity were measured in each session at the position of the participants. The average temperature and humidity values measured inside the test-room during the experiment were 20.7 ^{o}C and 38.3%. These values remained relatively constant throughout the duration of the experiment, whereby indoor temperature varied between 18.4 ^{o}C (minimum) and 22.5 ^{o}C (maximum) and humidity between 32.5% (minimum) and 46.0% (maximum), respectively. Across the five test sessions, temperature and humidity also remained relatively constant, whereby the maximum differences (i.e. maximum minus minimum) recorded when considered all test sessions that participants had taken part in were 1.7 ^{o}C and 2.6%, respectively.

The experimental procedure and duration are shown in Figure A3-2 and detailed in the Appendix. Upon arrival to the building, subjects read the experimental instructions, signed a consent form, completed a questionnaire surveying vision acuity (e.g., corrective lenses and reported colour blindness) and demographic, and completed the SSQ. The influence of individual differences caused by variations in demographics was counterbalanced by the repeated measure design; helping to reduce the influence of age on physiological responses collected from subjects [47, 57, 60]. Participants were required to abstain from intaking alcohol twenty-four hours and caffeine eight hours prior to the test [61]. To avoid unwanted symptoms that might be experienced from the VR, participants who suffer from migraines, epilepsy, motion sickness, sleep disorders, dizziness, or blurred vision were excluded from the study [62]. The actual purpose of this study remained vague to the participants until the experiment completion.

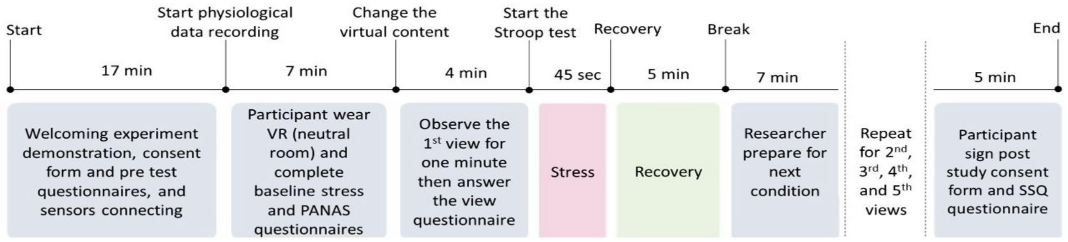

Figure A3-2. Overview of the experiment procedure from start to the end of a single test session

Participants were seated on a chair upon arrival to the test room and were instructed to limit their hand movement and to remain silent during the entire session to limit the noise in the recorded signals [63]. The researcher ensured that the physiological signals were correctly recording while participants familiarise themselves with the VR by observing the baseline neutral scene. When ready, participants were asked to answer the Stress and PANAS questionnaire to be used as a subjective baseline followed by five minutes recording of physiological baseline measurements, which was more than the recommended two minutes [44, 52, 54, 64]. The virtual content was then changed to the view corresponding to one of the window sizes (Figure A3-1), and participants observed the first view condition for one minute before answering the questions on view perception. Participants performed the Stroop test for 45 seconds [31] followed by another five minutes of physiological recovery measurements while observing the virtual window view. To be used as a subjective measure of recovery, participants answered the stress and PANAS questionnaire again.

A similar procedure was repeated until the five conditions were assessed and participants were given a seven-minute break between each condition [46, 63] (Figure A3-2).

A3.1.1.8 Statistical Analyses

Statistical analyses were conducted to analyse subjective and physiological responses. The test that was used to analyse the data depended on the data distributions and/or variances. The subjective and physiological data analysis was conducted for the full sample (n= 25). Physiological data was evaluated based on z-scores which is a recommended method to analyse physiological data [47, 65]. The original data was transformed to z-scores by subtracting the individual values from their sample mean and dividing this by the standard deviation.

Since questionnaires related to view perception and reported stress and PANAS were measured using a continuous scale, one-way repeated measure analysis of variance (ANOVA) test is adequate for data analysis when assumptions of normality of the sampling distributions and sphericity (i.e., the equality of variances across repeated conditions) are not violated [58]. Normality of the data about the mean was evaluated using the Kolmogorov-Smirnov [66] and Shapiro-Wilks [67] tests, while Sphericity was assessed using Mauchly’s test [68]. Whenever the assumption of normality was violated, the non-parametric Friedman’s ANOVA test was used [58], and proper correction of sphericity was applied (i.e., Huynh-Feldt or Greenhouse-Geisser corrections) to give conservative F-test statistic protected against Type I error [69] whenever sphericity assumption was violated [104]. To control the experimental-wise error rate, Bonferroni corrections were applied [58] for pairwise follow-up tests.

The effect sizes were reported along with statistical significance values to provide a standardised measure of the magnitude of the difference and to allow comparisons among similar studies [68]. The effect sizes Pearson's *r* and partial eta squared (η_p^2) were estimated from the inferential tests. Interpretation of the effect sizes was inferred using "small", "moderate" and "large" thresholds recommended by Ferguson [70]. a similar statistical analysis procedure was applied to analyse the physiological data.

To test the reliability of the view questionnaire (i.e., the survey items measured the same construct: view perception quality), the Cronbach's alpha (α) test [68] was used. The questionnaire had a high-reliability Cronbach's α= 0.97, attaining the accepted range (0.70-0.80) [68]. Therefore, the collected questionnaire items measured the same construct.

A3.1.2 Window Size Optimization for Energy and daylight Performance

A3.1.2.1 Climates

The simulation of different window sizes was computed using hourly averaged time steps for a year by applying International Weather for Energy Calculation (IWEC) files of three different climates: London, UK, as a temperate oceanic climate with mild summers and cool winters; Athens, Greece, as hot-summer mediterranean climate with hot-dry summers and mild winters; and Bangkok, Thailand, as a tropical climate with hot and humid summers, and warm winters. The locations' Köppen–Geiger climate classification [8], and their climatic properties including the temperature and horizontal solar radiation are described in Table A3-6 as retrieved from [71].

Table A3-6. Climatic properties of the different cities selected for simulation.

City	Climate	Location		Temperature (C°)		Solar radiation (kWh/m²/day)	
		latitude	longitude	Min.	Max.	Min.	Max.
London, UK	Cfb	51°15′ N	00°18′ W	0.85	22.05	0.70	4.84
Athens, Greece	Csa	37°58′ N	23°43' E	2.11	36.9	1.73	7.46
Bangkok, Thailand	Aw	13°75′ N	100°52′ E	19.65	35.65	4.49	6.23

The climates were selected to represent different latitudes, as with decreasing latitude of the cities, solar altitude (i.e., the angle of the Sun relative to the Earth's horizon) increases respectively, which might affect the available daylight accessing the building from windows. Therefore, with decreasing latitudes, cooling demands are mainly needed for south facing rooms (for Athens and Bangkok cases), while for increasing latitudes, heating demands are mainly required [4].

A3.1.2.2 Simulation Setup

An office-like test room used in the view perception experiment was modelled for the simulation. The room was located on the first floor and had a double-glazing window with 30% WWR (Figure A3-3). EnergyPlus software was used in this study to simulate predicted energy and daylight performance for different WWRs [72], and was selected for being a widely acknowledged software that has been developed via experimental analyses and tested according to ASHRAE Standard 140 evaluation method [73].

To evaluate the windows performance, WWR was simulated from 10 to 100% using 10% as step interval for simulation. The window was always centred in the wall to provide views with similar information (e.g., if the window was placed in the upper area of the wall, the resultant view provided might only include the sky). For the 20% and 10% WWRs, two layouts were evaluated to explore the window’s aspects ratio impact on windows performance including 20%W, 20%N, 10%W, and 10%N as shown in Figure A3-3. In the simulation model, adjacent offices were assumed to be conditioned uniformly and thermal requirements were determined to satisfy UK standards: for the thermal properties of the building envelope, the U-value was set as 0.28 W/m^2K for the external wall [74], and for all window sizes, a clear double-glazed window with U-value of 1.60 W/m^2K was [74] used and no shading devices were installed. Air change rate was set to 1.5/h. These values were kept consistent for all climates for consistency of the tested conditions.

Internal loads conditions and occupancy schedule represented a reference office: an occupant density is 12 m^2 per person [75] and the room was occupied between 9 am to 5 pm on workdays. Equipment and lighting loads were set to 15 W/m^2 and 7 W/m^2, respectively [76]. For heating and cooling, indoor temperatures of 21 ^oC, and 24 ^oC were used as thresholds for heating and cooling setpoints, respectively [76].

One illuminance sensor was positioned in the centre of the room (at the same position of the participant used in the view perception tests) to monitor the horizontal daylight illuminance and to control the artificial light supplementing natural light through an automatic dimmer (Figure A3-3). The sensor was placed at a working plane located 0.8 m from the floor and 2.18 m from the window, and an illuminance target of 300 lux was set as minimum illuminance required for standard office visual tasks [76].

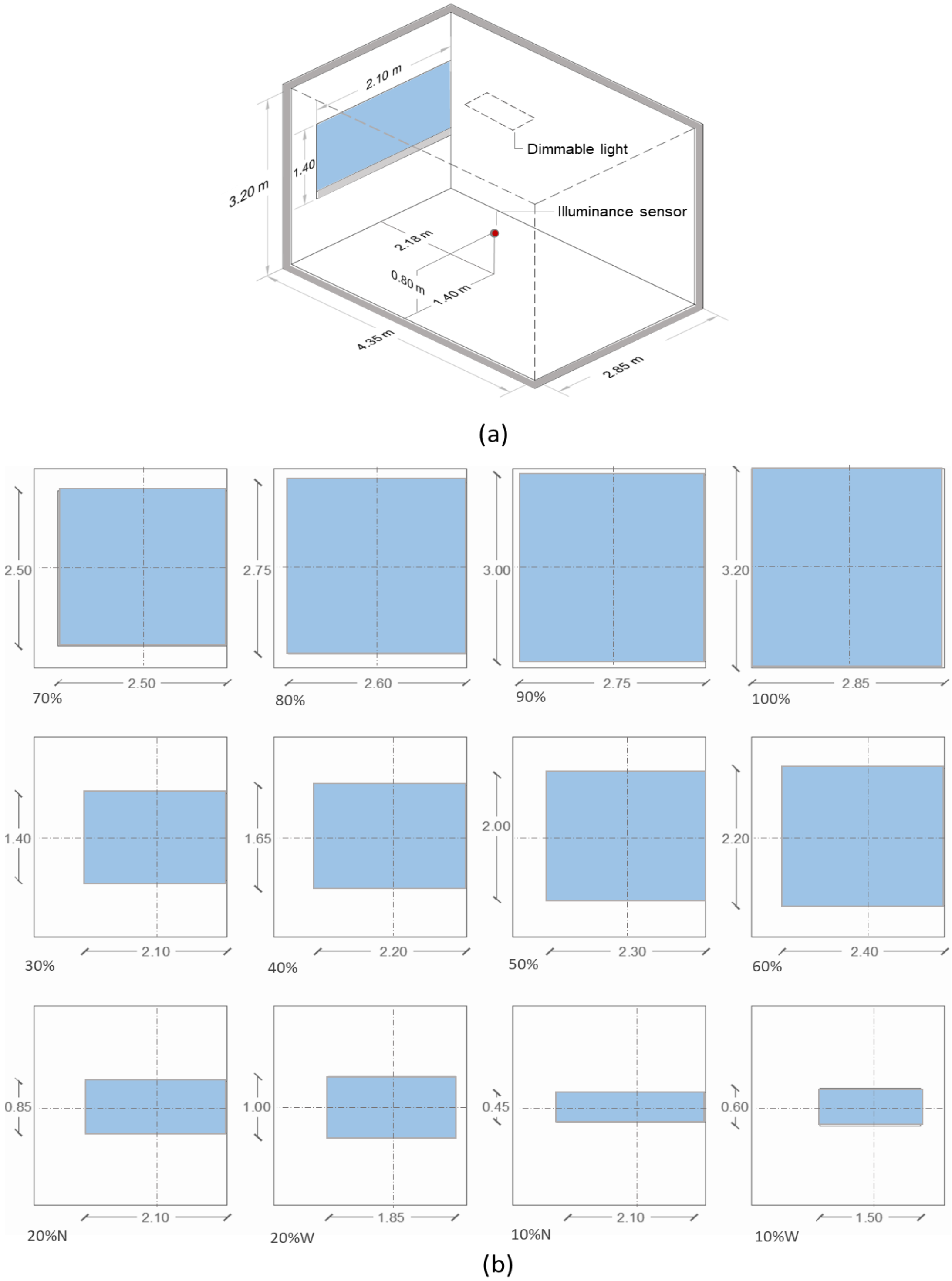

Figure A3-3. (a) The simulated room dimensions with sensors placement; (b) the examined window size variations used in the simulation.

A3.1.2.3 Optimization Evaluation Criteria

Total annual energy consumption and daylight performance criteria were used to evaluate the performance of different window sizes. Total energy consumption was simulated in terms of cooling, heating, and artificial lighting loads. For daylight performance, UDI [5] was used to assess based on the available amount of illuminance: the fraction of time during which indoor daylight illuminance at a certain point falls into one of the predetermined illuminance ranges [77]. In this study, illuminance levels were evaluated using <300 lux (UDI_{300}), 300≥and>2000 lux ($UDI_{300-2000}$), and ≥2000 lux (UDI_{2000}) for insufficient, sufficient, and potential glare benchmarks, respectively [78]. The minimum consumed energy was accepted to optimize the energy performance, whereas a 50% of the total occupancy time falling within $UDI_{300-2000}$ range was considered the threshold to meet the acceptance criteria for sufficient lighting [7]. The criteria used to optimize the window sizes performance and the corresponding acceptance values are indicated in Table A3-7.

Table A3-7. Summary of the window size optimization criteria

Evaluation criteria	Parameters	Unit	Acceptance value
Energy consumption	Heating demands Cooling demands Artificial lighting demands	kWh/m^2	Minimum energy consumption
Daylight	UDI	lux	50% of the total time during office occupancy falls in the sufficient category of $UDI_{300-2000}$

A3.2 Results

A3.2.1 Subjective Data on View Perception

Figure A3-4 presents the results of subjective view perception. The y-axis shows the rating by participants of view from 0 (Not at all) to 10 (Very much) for different perception parameters displayed on x-axis when presented with different window sizes: 30%, 20%W, 20%N, 10%W, and 10%N.

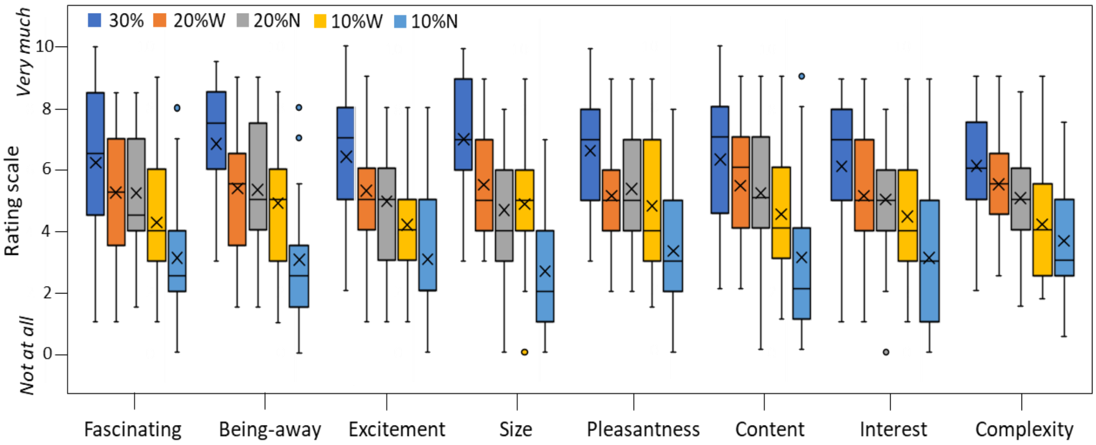

Figure A3-4. Boxplots of view perception parameters at each test session (variation of window size). Note: the crosses indicate the mean of the group condition.

As indicated in Figure A3-4, the statistical parameters (mean, minimum, 25th percentile, median, 75th percentile, and maximum) tend to correspond to higher ratings of view perception when considering the eight parameters and when participants were observing the view from larger windows.

The repeated-measures ANOVA test was used to compare the mean average evaluations given to the eight parameters of view perception across the five window conditions. Table A3-8 reports the F test statistic and the degrees of freedom (df), the statistical significance (p-value), and the effect size (η_p^2). The results from the ANOVA indicate highly significant differences for all eight parameters across the different conditions.

Table A3-8. ANOVA and effect sizes for each questionnaire items on view perception

Parameter	F (df)	p-value	Effect size (η_p^2)
Fascinating	13.34 (2.93)	0.00 ***	0.36

Being away	20.48 (4)	0.00 ***	0.46
Excitement	15.98 (2.67)	0.00***	0.40
Size	28.80 (4)	0.00 ***	0.54
Pleasantness	16.47 (2.98)	0.00 ***	0.41
Content	16.01 (4)	0.00 ***	0.40
Interest	11.19 (4)	0.00 ***	0.31
Complexity	16.44 (4)	0.00 ***	0.41

* weakly significant; ** significant; *** highly significant; n.s. not significant

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

Substantial effects were detected ($0.25<\eta_p^2\leq 0.64$) for all parameters. The analysis of the data suggests that for these parameters, the window size has a considerable influence on view perception. When the participant viewed the window view from the 30% window, they gave higher scores to the eight parameters. Further analysis using pairwise comparisons was performed to isolate the relevant differences in the analyses found in Table A3-8. The dependent *t*-test was used with Bonferroni adjustment for *p*-value (*p* is significant at 0.05 divided by number of paired comparisons) to control type I error of rejecting the null hypothesis when it is true [58]. Hence, an adjusted significant threshold of *p*-value (0.05/10=0.005) will be used to identify the significant criterion.

Table A3-9 presents the results of the pairwise comparisons for each questionnaire parameter, providing the mean and the standard deviation (SD) for the rating scores calculated at all test sessions, the difference between the means (ΔMean), the statistical significance (*p*-value), the test statistic (*t*), and the effect size (*r*).

Table A3-9. Pairwise comparisons between test sessions and effect sizes for each parameter

Parameter	Sessions	$Mean_1$ (SD)	$Mean_2$(SD)	ΔMean	*p*-value	*t* (df=24)	Effect size (*r*)

Fascinating	30 vs. 20W	6.21 (2.47)	5.23 (2.08)	0.98	0.02 n.s.	2.38	0.44
	30 vs. 20N	6.21 (2.47)	5.22 (2.17)	0.99	0.00 **	4.10	0.64
	30 vs. 10W	6.21 (2.47)	4.25 (2.15)	1.96	0.00 **	3.98	0.63
	30 vs. 10N	6.21 (2.47)	3.10 (2.05)	3.11	0.00 ***	5.55	0.75
	20W vs. 20N	5.23 (2.08)	5.22 (2.17)	0.01	0.98 n.s.	0.03	0.01
	20W vs. 10W	5.23 (2.08)	4.25 (2.15)	0.98	0.04 n.s.	2.18	0.41
	20W vs. 10N	5.23 (2.08)	3.10 (2.05)	2.13	0.00 **	3.83	0.62
	20N vs. 10W	5.22 (2.17)	4.25 (2.15)	0.97	0.02 n.s.	2.48	0.45
	20N vs. 10N	5.22 (2.17)	3.10 (2.05)	2.12	0.00 **	4.15	0.65
	10W vs. 10N	4.25 (2.15)	3.10 (2.05)	1.15	0.03 n.s.	2.30	0.42
Being away	30 vs. 20W	6.81 (2.06)	5.36 (2.10)	1.45	0.00 **	4.29	0.66
	30 vs. 20N	6.81 (2.06)	5.32 (2.18)	1.49	0.00 ***	5.19	0.73
	30 vs. 10W	6.81 (2.06)	4.88 (2.21)	1.93	0.00 **	4.74	0.70
	30 vs. 10N	6.81 (2.06)	3.04 (2.18)	3.77	0.00 ***	7.89	0.85
	20W vs. 20N	5.36 (2.10)	5.32 (2.18)	0.04	0.91 n.s.	0.11	0.02
	20W vs. 10W	5.36 (2.10)	4.88 (2.21)	0.48	0.29 n.s.	1.09	0.22
	20W vs. 10N	5.36 (2.10)	3.04 (2.18)	2.32	0.00 **	4.48	0.67
	20N vs. 10W	5.32 (2.18)	4.88 (2.21)	0.44	0.23 n.s.	1.24	0.25
	20N vs. 10N	5.32 (2.18)	3.04 (2.18)	2.28	0.00 **	4.45	0.67
	10W vs. 10N	4.88 (2.21)	3.04 (2.18)	1.84	0.00 **	4.13	0.64
Excitement	30 vs. 20W	6.38 (2.39)	5.28 (2.11)	1.10	0.01 n.s.	3.01	0.52
	30 vs. 20N	6.38 (2.39)	4.92 (2.10)	1.46	0.00 **	5.01	0.71
	30 vs. 10W	6.38 (2.39)	4.16 (2.13)	2.22	0.00 ***	5.46	0.74
	30 vs. 10N	6.38 (2.39)	3.04 (2.30)	3.34	0.00 ***	5.78	0.80
	20W vs. 20N	5.28 (2.11)	4.92 (2.10)	0.36	0.29 n.s.	1.07	0.21
	20W vs. 10W	5.28 (2.11)	4.16 (2.13)	1.12	0.02 n.s.	2.61	0.47
	20W vs. 10N	5.28 (2.11)	3.04 (2.30)	2.24	0.00 **	3.84	0.62
	20N vs. 10W	4.92 (2.10)	4.16 (2.13)	0.76	0.02 n.s.	2.52	0.46
	20N vs. 10N	4.92 (2.10)	3.04 (2.30)	1.88	0.00 **	3.59	0.59
	10W vs. 10N	4.16 (2.13)	3.04 (2.30)	1.12	0.03 n.s.	3.01	0.43
Size	30 vs. 20W	7.02 (1.90)	5.52 (1.91)	1.50	0.00 **	4.42	0.67
	30 vs. 20N	7.02 (1.90)	4.68 (2.15)	2.34	0.00 ***	6.98	0.82
	30 vs. 10W	7.02 (1.90)	4.88 (2.11)	2.14	0.00 ***	5.15	0.72
	30 vs. 10N	7.02 (1.90)	2.68 (2.03)	4.34	0.00 ***	9.24	0.88
	20W vs. 20N	5.52 (1.91)	4.55 (2.46)	0.84	0.05 n.s.	2.06	0.39
	20W vs. 10W	5.52 (1.91)	4.88 (2.11)	0.64	0.17 n.s.	1.40	0.27
	20W vs. 10N	5.52 (1.91)	2.68 (2.03)	2.84	0.00 ***	6.16	0.80
	20N vs. 10W	4.55 (2.46)	4.88 (2.11)	-0.20	0.48 n.s.	-0.72	0.15
	20N vs. 10N	4.55 (2.46)	2.68 (2.03)	2.00	0.00 **	4.11	0.64
	10W vs. 10N	4.88 (2.11)	2.68 (2.03)	2.20	0.00 ***	5.09	0.72
Pleasantness	30 vs. 20W	6.64 (2.25)	5.16 (2.13)	1.48	0.00 **	3.86	0.62
	30 vs. 20N	6.64 (2.25)	5.38 (2.18)	1.26	0.00 ***	5.49	0.75
	30 vs. 10W	6.64 (2.25)	4.82 (2.29)	1.82	0.00 **	4.71	0.69
	30 vs. 10N	6.64 (2.25)	3.34 (2.36)	3.30	0.00 ***	7.47	0.84
	20W vs. 20N	5.16 (2.13)	5.38 (2.18)	-0.22	0.56 n.s.	-0.59	0.12
	20W vs. 10W	5.16 (2.13)	4.82 (2.29)	0.34	0.40 n.s.	0.85	0.17
	20W vs. 10N	5.16 (2.13)	3.34 (2.36)	1.82	0.00 *	3.50	0.58
	20N vs. 10W	5.38 (2.18)	4.82 (2.29)	0.56	0.09 n.s.	1.79	0.34
	20N vs. 10N	5.38 (2.18)	3.34 (2.36)	2.04	0.00 **	4.23	0.65
	10W vs. 10N	4.82 (2.29)	3.34 (2.36)	1.48	0.01 n.s.	2.86	0.50

Content	30 vs. 20W	6.26 (2.25)	5.40 (2.06)	0.86	0.02 n.s.	2.40	0.44
	30 vs. 20N	6.26 (2.25)	5.16 (2.23)	1.10	0.00 *	3.51	0.58
	30 vs. 10W	6.26 (2.25)	4.46 (2.35)	1.80	0.00 *	3.81	0.61
	30 vs. 10N	6.26 (2.25)	3.04 (2.47)	3.22	0.00 ***	6.86	0.81
	20W vs. 20N	5.40 (2.06)	5.16 (2.23)	0.24	0.46 n.s.	0.74	0.15
	20W vs. 10W	5.40 (2.06)	4.46 (2.35)	0.94	0.02 n.s.	2.50	0.45
	20W vs. 10N	5.40 (2.06)	3.04 (2.47)	2.36	0.00 ***	4.96	0.71
	20N vs. 10W	5.16 (2.23)	4.46 (2.35)	0.70	0.11 n.s.	1.66	0.32
	20N vs. 10N	5.16 (2.23)	3.04 (2.47)	2.12	0.00**	4.48	0.67
	10W vs. 10N	4.46 (2.35)	3.04 (2.47)	1.42	0.01 n.s.	2.73	0.50
Interest	30 vs. 20W	6.12 (2.30)	5.16 (2.07)	0.96	0.03 n.s.	2.34	0.43
	30 vs. 20N	6.12 (2.30)	5.04 (1.92)	1.08	0.01 n.s.	3.04	0.53
	30 vs. 10W	6.12 (2.30)	4.48 (2.22)	1.64	0.00 **	4.34	0.66
	30 vs. 10N	6.12 (2.30)	3.12 (2.55)	3.00	0.00 ***	5.02	0.72
	20W vs. 20N	5.16 (2.07)	5.04 (1.92)	0.12	0.76 n.s.	0.31	0.06
	20W vs. 10W	5.16 (2.07)	4.48 (2.22)	0.68	0.13 n.s.	1.58	0.31
	20W vs. 10N	5.16 (2.07)	3.12 (2.55)	2.04	0.00 *	3.35	0.56
	20N vs. 10W	5.04 (1.92)	4.48 (2.22)	0.56	0.10 n.s.	1.69	0.33
	20N vs. 10N	5.04 (1.92)	3.12 (2.55)	1.92	0.00 *	3.72	0.60
	10W vs. 10N	4.48 (2.22)	3.12 (2.55)	1.36	0.02 n.s.	2.53	0.46
Complexity	30 vs. 20W	6.08 (1.87)	5.48 (1.81)	0.60	0.03 n.s.	2.38	0.44
	30 vs. 20N	6.08 (1.87)	5.04 (1.73)	1.04	0.00**	3.74	0.61
	30 vs. 10W	6.08 (1.87)	4.17 (1.82)	1.91	0.00 ***	6.12	0.80
	30 vs. 10N	6.08 (1.87)	3.64 (1.80)	2.44	0.00 ***	5.68	0.80
	20W vs. 20N	5.48 (1.81)	5.04 (1.73)	0.44	0.13 n.s.	1.55	0.30
	20W vs. 10W	5.48 (1.81)	4.17 (1.82)	1.31	0.00 **	4.28	0.66
	20W vs. 10N	5.48 (1.81)	5.04 (1.73)	1.84	0.00 **	4.45	0.67
	20N vs. 10W	5.04 (1.73)	4.17 (1.82)	0.87	0.02 n.s.	2.41	0.44
	20N vs. 10N	5.04 (1.73)	5.04 (1.73)	1.40	0.00*	3.69	0.60
	10W vs. 10N	4.17 (1.82)	5.04 (1.73)	0.53	0.16 n.s.	1.45	0.28

Bonferroni corrected: * weakly significant; ** significant; *** highly significant; n.s. not significant
$r<0.20$ = negligible; $0.20 \leq r<0.50$ = small; $0.50 \leq r<0.80$ = moderate; $r \geq 0.80$ = large

The pairwise comparisons provide evidence that the differences between subjective rating scores, reported when observing the view from different window sizes, are highly significant in 17 cases, significant in 22 cases, weakly significant in 6 cases, and not significant in 35 cases out of a total of 80 comparisons. The differences have "large" effect sizes in 9 cases, "moderate" effect sizes in 40 cases, "small" in 24 cases, and negligible ($r<0.20$) in 7 cases out of 80. For all parameters, the largest statistically significant differences and largest effect sizes were detected between the 30% and all remaining window sizes. Smaller effect sizes occurred for questionnaire items between 20%W and 20%N except for size and complexity parameters which had moderate effect sizes, however, were not statistically significant. Window view with 10%N size was perceived significantly different for all view parameters when compared to other window sizes with moderate and large effect sizes, except when compared to 10%W, as the effect sizes ranged from small to moderate. These effect sizes were considered to avoid type II error (i.e., failure to reject the null hypothesis when it is false) as the increase of the sample size may lead to significant results [79]. Therefore, the analysis of the data suggests that for these parameters, the size of the window has a direct influence on view perception with substantive magnitude between 30% window and 20%W, 20%N, 10%W, and 10%N, and smaller magnitudes between the similar WWRs (i.e., between 20%W and 20%N; and between 10%W and 10%N).

The view "fascinating" was perceived fairly higher for the 30% condition compared to 20%W ($0.20 \leq r < 0.50$), and substantially higher compared to 20%N and 10%W conditions ($0.5 \leq r < 0.8$) and to 10%N condition ($r \geq 0.8$). The view's fascination was perceived higher for 20%W and 20%N compared to 10%W condition with small magnitude ($0.20 \leq r < 0.50$), and was perceived substantially higher compared to 10%N. For windows with similar WWR, the decrease in view fascinating was negligible between 20%W and 20%N conditions ($r < 0.20$) and was small between 10%W and 10%N ($0.20 \leq r < 0.50$)."Being away" item was perceived substantially higher for the 30% condition compared to 20%W, 20%N, and 10%W conditions ($0.5 \leq r < 0.8$), and to 10%N condition ($r \geq 0.8$). This item was perceived higher for 20%W and 20%N compared to 10%W condition with small magnitude ($0.20 \leq r < 0.50$), and was perceived substantially higher compared to 10%N. For windows with similar WWR, the decrease in “being away” rating was negligible between 20%W and 20%N conditions ($r<0.20$) and was substantial between 10%W and 10%N ($0.5 \leq r<0.8$).

View “content” showed a similar trend. Content preference was rated fairly higher for the 30% condition compared to 20%W ($0.20 \leq r<0.50$), and substantially higher compared to 20%N and 10%W conditions ($0.5 \leq r<0.8$) and to 10%N condition ($r \geq 0.8$); indicating a significant decrease in satisfaction with view content as the window size decreased. This Item was rated higher for 20%W and 20%N compared to 10%W condition with small magnitude ($0.20 \leq r<0.50$), and substantially higher compared to 10%N. For similar WWR windows, the decrease in view content preference was negligible between 20%W and 20%N conditions ($r<0.20$) and was moderate between 10%W and 10%N ($r=0.5$).

Satisfaction with view size was rated substantially higher for the 30% condition compared to 20%W and 10%W ($0.5 \leq r<0.8$), and with higher magnitude compared to 20%N and 10%N conditions ($r \geq 0.8$). The view’s size preference was rated higher for 20%W and 20%N compared to the 10%W condition with small magnitude ($0.20 \leq r<0.50$), and was rated substantially higher compared to 10%N ($0.5 \leq r<0.8$) with a higher magnitude between 20%W and 10%W ($r \geq 0.8$). For windows with similar WWR, the decrease in size preference rating was slight between 20%W and 20%N conditions ($0.20 \leq r<0.50$) and was substantial between 10%W and 10%N ($0.5 \leq r<0.8$).

Perception of view interest showed significantly higher ratings for the 30% condition compared to 20%N, 10%W, and 10%N conditions ($0.5 \leq r<0.8$), and slightly higher compared to the 20%W condition ($0.20 \leq r<0.50$). The view’s perceived interest preference was rated lower for 20%W and 20%N conditions compared to the 10%W condition with small magnitude ($0.20 \le r < 0.50$), and was perceived substantially higher compared to 10%N ($0.5 \le r < 0.8$). For similar WWR windows, the decrease was negligible between 20%W and 20%N conditions ($r < 0.20$) and was small between 10%W and 10%N ($0.20 \le r < 0.50$).

The perceived complexity of the view showed slightly higher ratings for the 30% condition compared to 20%W ($0.20 \le r < 0.50$), moderately higher ratings compared to 20%N ($0.5 \le r < 0.8$), and substantially higher ratings compared to both 10% WWRs ($r \ge 0.8$). The view's complexity was rated substantially higher for the 20%W condition compared to 10%W ($0.5 \le r < 0.8$), and slightly higher for 20%N compared to 10%W with small magnitude ($0.20 \le r < 0.50$), and both 20% WWRs were perceived substantially higher compared to 10%N ($0.5 \le r < 0.8$). For similar WWR windows, the decrease in view complexity was small ($0.20 \le r < 0.50$).

View valance/arousal was also differently perceived amongst the different conditions. Figure A3-5 indicates the change in mean ratings on the valance/arousal Circumplex model of affects. The locations of mean rating demonstrate the change in perceived affects corresponding to each WWR condition. When participants observed the 30% window in the virtual environment, they reported more pleasantness and arousal compared to other WWRs with moderate and large effect sizes. The 30% WWR suggests that there was a stimulating affect. However, the mean ratings of view perception given to the remaining WWRs in terms of arousal/valance shifted towards the dull criterion, which is associated with lower arousal and lower pleasantness resulting in a less stimulating working environment. For similar WWRs, the arousal/valance ratings were similar between 20%W and 20%N with small and negligible effect sizes for arousal and pleasantness, respectively; whereas between the

10%W and 10%N conditions, the differences were higher with small and moderate magnitudes for arousal and pleasantness, respectively.

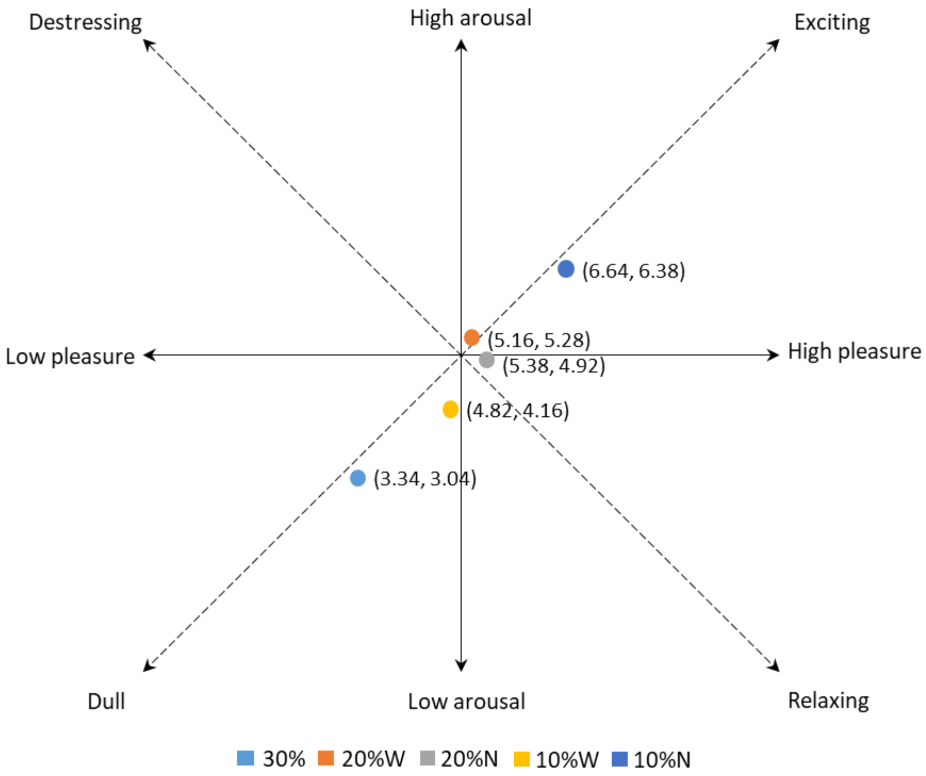

Figure A3-5. Locations of mean ratings of view perceived valance/arousal on the Circumplex model of affects adopted from [80]

A3.2.2 Self-Reported Stress and PANAS

The results of Friedman's ANOVA statistical analysis indicated significant differences in recovery from the stress when compared to the baseline when participants were exposed to the window view from different WWRs in terms of self-reported stress (ΔStress) $\chi^2(4)=19.65$, $p<0.01$**, positive affects (ΔPA) $\chi^2(4)=16.99$, $p<0.01$**, and negative affects (ΔNA) $\chi^2(4)= 14.58$, $p<0.01$**. Pairwise comparisons using Wilcoxon signed-rank test were conducted to determine the magnitude of differences in ΔStress, ΔPA, and ΔNA across the five different conditions. Table A3-10 reports the median (M_{dn}), the interquartile range (IQR), the associated significance (*p*-value), the (positive) and (negative) ranks, the ties, and the calculated effect sizes (*r*).

Table A3-10. Wilcoxon signed-rank tests and effect sizes for subjective recovery parameters

Parameter	Conditions	M_{1dn} (IQR)	M_{2dn} (IQR)	*p*-value	Negative	Positive	Ties	z	*r*
ΔStress	30 vs. 20W	0.00 (20.00)	1.00 (17.50)	0.03 n.s.	13	5	7	-2.18	-0.31
	30 vs. 20N	0.00 (20.00)	0.00 (13.00)	0.10 n.s.	13	4	8	-1.64	-0.23
	30 vs. 10W	0.00 (20.00)	0.00 (11.00)	0.02 n.s	14	3	8	-2.31	-0.33
	30 vs. 10N	0.00 (20.00)	10.00 (20.00)	0.00 ***	18	2	5	-3.73	-0.53
	20W vs. 20N	1.00 (17.50)	0.00 (13.00)	0.13 n.s.	7	11	7	-1.52	-0.22
	20W vs. 10W	1.00 (17.50)	0.00 (11.00)	0.98 n.s.	8	8	9	-0.03	-0.00
	20W vs. 10N	1.00 (17.50)	10.00 (20.00)	0.23 n.s.	12	4	9	-1.19	-0.17
	20N vs. 10W	0.00 (13.00)	0.00 (11.01)	0.09 n.s.	11	8	6	-1.68	-0.24
	20N vs. 10N	0.00 (13.00)	10.00 (20.00)	0.01 n.s.	15	5	5	-2.48	-0.35
	10W vs. 10N	0.00 (11.00)	10.00 (20.00)	0.13 n.s.	13	4	8	-1.52	-0.22
ΔPA	30 vs. 20W	1.00 (6.50)	1.00 (4.00)	0.59 n.s.	11	10	4	-0.54	-0.08
	30 vs. 20N	1.00 (6.50)	-1.00 (6.00)	0.00 *	4	18	3	-2.82	-0.40
	30 vs. 10W	1.00 (6.50)	-1.00 (6.50)	0.01 n.s.	6	16	3	-2.69	-0.38
	30 vs. 10N	1.00 (6.50)	-2.00 (6.00)	0.00 ***	5	17	3	-3.50	-0.49
	20W vs. 20N	1.00 (4.00)	-1.00 (6.00)	0.05 n.s.	6	17	2	-1.93	-0.27
	20W vs. 10W	1.00 (4.00)	-1.00 (6.50)	0.05 n.s.	6	15	4	-1.95	-0.28
	20W vs. 10N	1.00 (4.00)	-2.00 (6.00)	0.00 *	6	16	3	-3.15	-0.44
	20N vs. 10W	-1.00 (6.00)	-1.00 (6.50)	0.58 n.s.	8	11	6	-0.55	-0.08
	20N vs. 10N	-1.00 (6.00)	-2.00 (6.00)	0.05 n.s.	8	13	4	-1.99	-0.28
	10W vs. 10N	-1.00 (6.50)	-2.00 (6.00)	0.05 n.s.	7	14	4	-1.96	-0.28
ΔNA	30 vs. 20W	0.00 (3.00)	0.00 (3.00)	0.05 n.s	13	4	8	-1.97	-0.28
	30 vs. 20N	0.00 (3.00)	0.00 (3.50)	0.75 n.s	9	5	11	-0.32	-0.04
	30 vs. 10W	0.00 (3.00)	0.00 (3.50)	0.06 n.s	11	4	10	-1.92	-0.27
	30 vs. 10N	0.00 (3.00)	0.00 (3.50)	0.00 *	15	3	7	-2.89	-0.41
	20W vs. 20N	0.00 (3.00)	0.00 (3.50)	0.08 n.s	5	10	10	-1.78	-0.25
	20W vs. 10W	0.00 (3.00)	0.00 (3.50)	0.96 n.s	8	8	9	-0.05	-0.01
	20W vs. 10N	0.00 (3.00)	0.00 (4.00)	0.27 n.s	13	7	5	-1.11	-0.16
	20N vs. 10W	0.00 (3.50)	0.00 (4.00)	0.33 n.s	9	6	10	-0.98	-0.14
	20N vs. 10N	0.00 (3.50)	0.00 (4.00)	0.00 *	13	2	10	-2.88	-0.41
	10W vs. 10N	0.00 (3.50)	0.00 (4.00)	0.18 n.s	13	6	6	-1.35	-0.19

* weakly significant; ** significant; *** highly significant; n.s. not significant
r<0.20 = negligible; 0.20≤r<0.50 = small; 0.50≤r<0.80 = moderate; r≥0.80 = large

The Wilcoxon signed-rank tests indicate that the differences between subjective recovery parameters reported when observing the view from different window sizes are not significant in 24 cases, highly significant in 2 cases, and weakly significant in 4 cases out of 30. Detected effect sizes were negligible in 9 cases (r<0.2), small in 20 cases (0.2≤r<0.5), and moderate (0.5≤r<0.8) in 1 case out of 30.

For ΔStress, small and moderate effect sizes were detected between 30% and remaining conditions with the largest effect when compared to 10%N (0.5≤r<0.8), indicating an improved stress recovery when observing the view from 30% window. Reported recovery for 20% WWRs compared to 10% WWRs are minor with small and negligible effect sizes. Comparison between similar WWRs revealed similar recovery rates (0.2≤r<0.5). the results indicated a similar recovery for this parameter for 20% and 10% WWRs. ΔPA decrease was similar for 30% and 20%W (r<0.2). Both conditions showed slightly improved values compared to other WWRs (0.2≤r<0.5). ΔPA was similar for 20%N and 10%W, both showing improved values compared to 10%N condition (0.2≤r<0.5). ΔNA was similar for 30% and 20%N (r<0.2). Both conditions showed a decrease in NA values compared to other WWRs (0.2≤r<0.5). The reported ΔNA was similar between 20%W, 10%W, and 10%N with small and negligible effect sizes.

Therefore, it can be inferred that window size affected the reported recovery from stress with small to moderate magnitudes with enhanced recovery in stress and PANAS for 30% and 20% WWR conditions. This was donated by the effect sizes and by the large numbers of positive ranks in PA comparisons and large numbers of negative ranks in stress and NA results. Stress recovery using physiological data was analysed to assess whether the same results will be inferred and to provide an objective measure to stress recovery.

A3.2.3 Physiological Data

A3.2.4 Variations in Initial Response to View

Friedman's ANOVA statistical analysis showed no significant difference when the participants first observed the view for different conditions in SCR $\chi^2(4)=2.94$, $p>0.05$, HF-HRV $\chi^2(4)= 4.99$, $p>0.05$, LF/HF $\chi^2(4)= 3.52$, $p>0.05$, and BVA $\chi^2(4)= 3.42$, $p>0.05$; therefore, no further analysis was conducted for those measures. However, LF-HRV showed significant difference $\chi^2(4)= 13.28$, $p<0.01$*. For the initial response using HR and HRV measures, One-way repeated measure ANOVA statistical analysis showed no significant difference in HR $F(4,96)= 0.70$, $p>0.05$ whilst significant difference was detected in HRV_a data $F(4,96)= 3.95$, $p<0.01$** with small effect ($0.04<\eta_p^2\leq0.25$). Therefore, pairwise comparisons were conducted for LF-HRV and HRV_a to explore the magnitude of differences across the five different conditions.

Wilcoxon signed-rank tests were conducted for LF-HRV. Table A3-11 reports the median (M_{dn}), the interquartile range (IQR), the associated significance (p-value), the (positive) and (negative) ranks, the ties, and the calculated effect sizes (r).

Table A3-11. Wilcoxon signed-rank tests and effect sizes for LF-HRV

Parameter	Conditions	M_{1dn} (IQR)	M_{2dn} (IQR)	*p*-value	Negative	Positive	Ties	z	*r*
LF-HRV	30 vs. 20W	0.14 (0.48)	0.00 (0.19)	0.07	7	18	0	-1.84	-0.26
	30 vs. 20N	0.14 (0.48)	0.00 (0.56)	0.07	8	17	0	-1.82	-0.26
	30 vs. 10W	0.14 (0.48)	0.08 (0.25)	0.51	10	15	0	-0.66	-0.09
	30 vs. 10N	0.14 (0.48)	-0.05 (0.18)	0.05	7	18	0	-2.01	-0.28
	20W vs. 20N	-0.05 (3.00)	0.00 (0.56)	0.74	5	10	0	-0.34	-0.05
	20W vs. 10W	0.00 (0.19)	0.08 (0.25)	0.02	16	9	0	-2.25	-0.32
	20W vs. 10N	0.00 (0.19)	-0.05 (0.18)	0.49	16	9	0	-0.69	-0.10
	20N vs. 10W	0.00 (0.56)	0.08 (0.25)	0.44	10	15	0	-0.77	-0.11
	20N vs. 10N	0.00 (0.56)	-0.05 (0.18)	0.70	12	13	0	-0.39	-0.06
	10W vs. 10N	0.08 (0.25)	-0.05 (0.18)	0.00*	4	21	0	-3.00	-0.42

* weakly significant; ** significant; *** highly significant; n.s. not significant
r<0.20 = negligible; 0.20≤r<0.50 = small; 0.50≤r<0.80 = moderate; r≥0.80 = large

The results indicate that the differences in LF-HRV in different conditions are weakly significant in 1 case, and not significant in 9 out of 10 cases. Detected effect sizes were negligible in 5 cases (r<0.2), and small in 5 cases out of 10. LF-HRV was slightly higher (0.20≤r<0.50) when participants first observed the view from 30% window compared to the remaining WWRs as indicated by the high number of negative ranks except to 10%W (r<0.2), which suggests higher arousing affect for these two conditions. For 20%W, the LF-HRV was similar compared to 20%N and 10%N conditions (r<0.2), and slightly lower compared to 10%W (0.20≤r<0.50). The LF-HRV level with 20%N was similar to 10%W and 10%N conditions (r<0.2), while 10%W resulted in fair increase in LF-HRV compared to 10%N (0.20≤r<0.50).

Table A3-12 presents the results of the *t*-test pairwise comparisons for HRV_a initial response to views, providing the mean and the standard deviation (SD) for the scores calculated at all test sessions, the difference between the means (ΔMean), the statistical significance (*p*-value), the test statistic (*t*), and the effect size (*r*).

Table A3-12. Pairwise comparisons between test sessions and effect sizes for each parameter

Parameter	Sessions	$Mean_1$ (SD)	$Mean_2$ (SD)	ΔMean	*p*-value	*t* (df=24)	Effect size (r)
HRV_a	30 vs. 20W	-0.22 (0.52)	-0.21 (0.41)	0.00	0.98 n.s.	-0.03	0.01
	30 vs. 20N	-0.22 (0.52)	-0.04 (0.40)	-0.18	0.16 n.s.	-1.46	0.28
	30 vs. 10W	-0.22 (0.52)	-0.06 (0.35)	-0.28	0.04 n.s.	-2.12	0.40
	30 vs. 10N	-0.22 (0.52)	0.13 (0.49)	-0.34	0.00 *	-2.94	0.51
	20W vs. 20N	-0.21 (0.41)	-0.04 (0.40)	-0.17	0.09 n.s.	-1.77	0.34
	20W vs. 10W	-0.21 (0.41)	-0.06 (0.35)	-0.28	0.01 n.s.	-2.69	0.48
	20W vs. 10N	-0.21 (0.41)	0.13 (0.49)	-0.34	0.00 *	-2.93	0.51
	20N vs. 10W	-0.04 (0.40)	-0.06 (0.35)	-0.10	0.27 n.s.	-1.13	0.22
	20N vs. 10N	-0.04 (0.40)	0.13 (0.49)	-0.17	0.14 n.s.	-1.53	0.30
	10W vs. 10N	-0.06 (0.35)	0.13 (0.49)	-0.06	0.54 n.s.	-0.62	0.13

* weakly significant; ** significant; *** highly significant; n.s. not significant
<0.20 = negligible; 0.20≤r<0.50 = small; 0.50≤r<0.80 = moderate; r≥0.80 = large

The pairwise comparisons provide evidence that the differences in HRV_a data collected during view observing from different WWRs are weakly significant in 2 cases and non-significant in 8 cases out of 10 comparisons. The differences have moderate magnitude ($0.50 \leq r < 0.80$) in 2 cases, small magnitudes ($0.20 \leq r < 0.50$) in 6 cases, and negligible ($r < 0.20$) in 2 cases out of 10. In general, the HRV_a was decreasing for the larger WWRs, which suggests more cognitive work. HRV_a was similar for the 30% condition compared to 20%W ($r < 0.20$), and both were fairly lower compared to 20%N and 10%W conditions ($0.20 \leq r < 0.50$), and moderately lower compared to 10%N condition ($0.50 \leq r < 0.80$). HRV_a was slightly lower for 20%N compared to 10%W and 10%N ($0.20 \leq r < 0.50$) and was similar between 10% WWRs.

A3.2.5 Physiological Stress and Recovery Measurements

Figure A3-6 indicates the results of SCL during recovery and stress induction. The y-axis shows SCL for stress and recovery periods displayed on x-axis when performed with different window sizes: 30%, 20%W, 20%N, 10%W, and 10%N. The statistical parameters (mean, minimum, 25th percentile, median, 75th percentile, and maximum) tend to correspond to a higher SCL value when participants were observing the view from 10%N window. ANOVA test was used to compare the SCL data during stress and recovery across the five conditions and the results indicate that stress levels during task performance were similar across all conditions $F(4,96) = 13.34$, $p > 0.05$ with negligible effect and no further analysis was conducted. Recovery data results indicate a significant difference across the different conditions $F(4,96) = 20.48$, $p < 0.05$* with small effect detected.

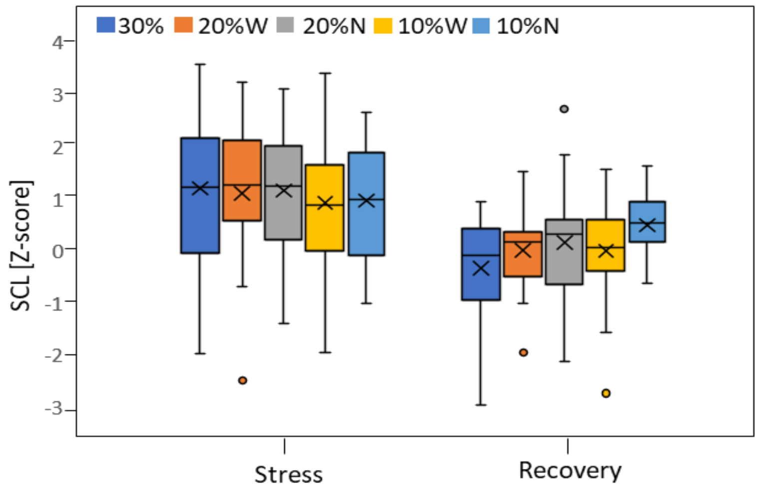

Figure A3-6. Boxplots of SCL at each test session (variation of window size). Note: the crosses indicate the mean of the group condition.

To identify which observing location has affected the SCL, dependent *t*-test pairwise comparisons were used. Table A3-13 presents the results of the pairwise comparisons for each questionnaire parameter, providing the mean and the standard deviation (SD) for the rating scores calculated at all test sessions, the difference between the means (ΔMean), the statistical significance (*p*-value), the test statistic (*t*), and the effect size (*r*).

Table A3-13. Pairwise comparisons between test sessions and effect sizes for each parameter

Parameter	Sessions	$Mean_1$ (SD)	$Mean_2$ (SD)	ΔMean	*p*-value	*t* (df=24)	Effect size (r)
Recovery SCL	30 vs. 20W	-0.33 (1.09)	0.01 (0.86)	-0.34	0.21 n.s.	-1.28	0.25
	30 vs. 20N	-0.33 (1.09)	0.17 (1.08)	-0.49	0.11 n.s.	-1.66	0.32
	30 vs. 10W	-0.33 (1.09)	0.00 (0.91)	-0.33	0.30 n.s.	-1.07	0.21
	30 vs. 10N	-0.33 (1.09)	0.50 (0.59)	-0.82	0.00 *	-3.28	0.56
	20W vs. 20N	0.01 (0.86)	0.17 (1.08)	-0.15	0.61 n.s.	-0.51	0.10
	20W vs. 10W	0.01 (0.86)	0.00 (0.91)	0.01	0.95 n.s.	0.07	0.01
	20W vs. 10N	0.01 (0.86)	0.50 (0.59)	-0.48	0.02 n.s.	-2.41	0.44
	20N vs. 10W	0.17 (1.08)	0.00 (0.91)	0.16	0.56 n.s.	0.59	0.12
	20N vs. 10N	0.17 (1.08)	0.50 (0.59)	-0.33	0.20 n.s.	-1.32	0.26
	10W vs. 10N	0.00 (0.91)	0.50 (0.59)	-0.49	0.03 n.s.	-2.26	0.42

* weakly significant; ** significant; *** highly significant; n.s. not significant
r<0.20= negligible; 0.20≤r<0.50= small; 0.50≤r<0.80= moderate; r≥0.80= large

The pairwise comparisons provide evidence that the differences in SCL data, collected during recovery with different window sizes conditions are not significant in 1 case out of 10 comparisons. The differences have moderate magnitude ($0.50 \leq r < 0.80$) in 1 case, small ($0.20 \leq r < 0.50$) in 6 cases, and negligible ($r < 0.20$) in 3 cases out of 10.

During the recovery, the analysis suggests that stress measured by SCL was slightly lower for the 30% condition compared to 20%W, 20%N, and 10%W conditions ($0.2 \leq r < 0.5$), and substantially higher compared to 10%W condition ($0.50 \leq r < 0.80$), indicating a significant decrease in recovery from stress as window size decreases. However, the decrease in recovery rates using SCL were similar between 20%W, 20%N, and 10%W conditions, as indicated by negligible effect sizes ($r < 0.20$). Nevertheless, 20%W, 20%N, and 10%W conditions showed slightly enhanced recovery rates compared to 10%N. Overall, the results indicate the lowest recovery rates when participants were observing the view from 10%N. These results are similar to those provided by the subjective recovery in Table A3-10 suggesting that after a certain amount of information is provided by the view (i.e., due to increased WWR or changing layout), recovery rates will be similar.

Figure A3-7 indicates the results of HR and HRV measures including HRV_a, BVA, LF-HRV, HF-HRV, and LF/HF. The y-axis shows the scores of these measures during stress and recovery periods displayed on the x-axis when performed with different window sizes: 30%, 20%W, 20%N, 10%W, and 10%N.

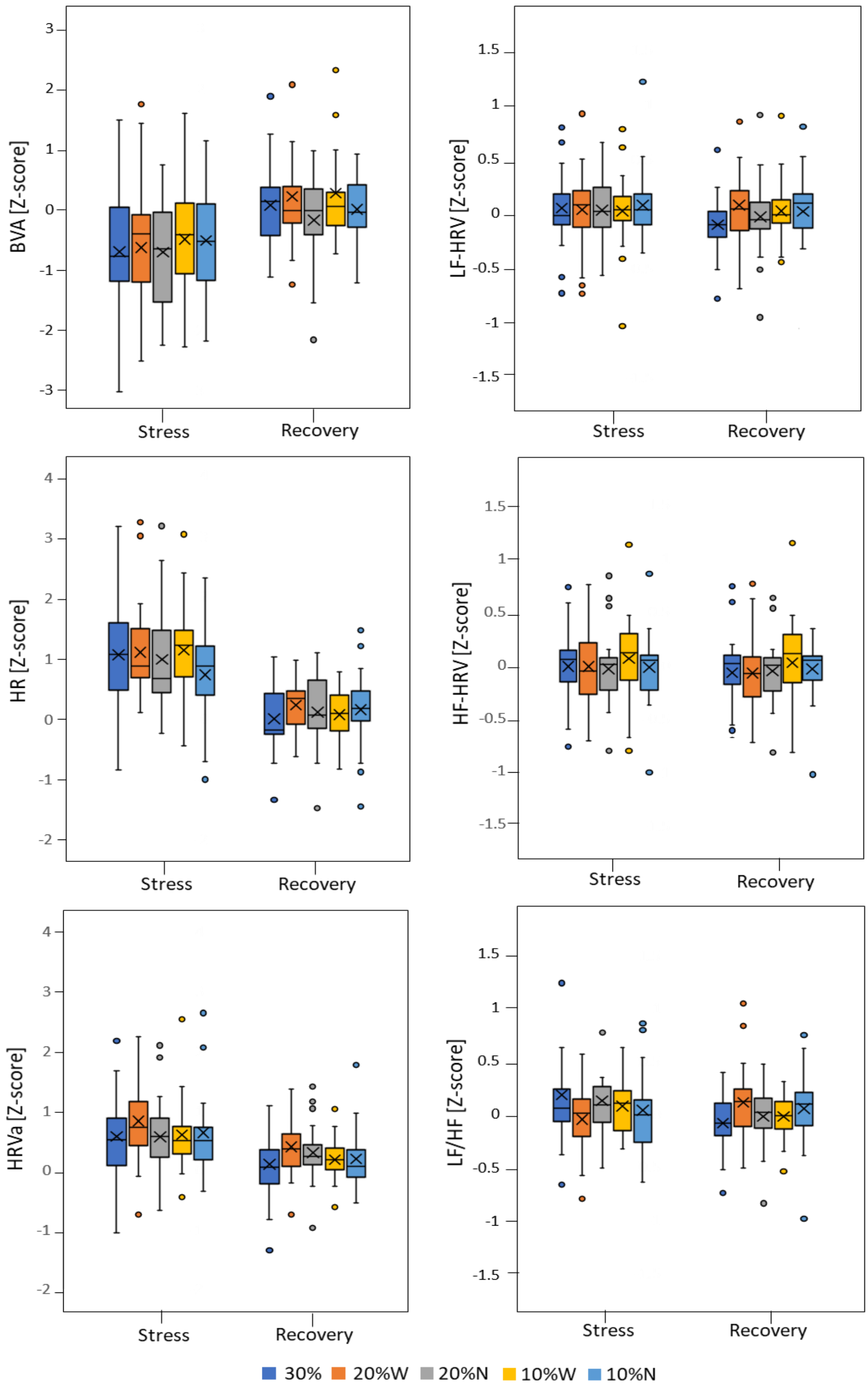

Figure A3-7. Boxplots of HR and HRV parameters at each test session (variation of window size). Note: the crosses indicate the mean of the group condition.

The statistical parameters (mean, minimum, 25th percentile, median, 75th percentile, and maximum) tend to correspond to lower recovery value when participants were observing the view from 30% window in HR, HRV_a, LF-HRV, and LF/HF.

ANOVA test was used to compare the HR, LF-HRV, HF-HRV, and HRVa data for the different conditions. Table A3-14 reports the results from the ANOVA, indicating the *F* test statistic and the degrees of freedom (df), the statistical significance (*p*-value), and the effect size partial eta squared (η_p^2).

Table A3-14. ANOVA and effect sizes for each parameter

Parameter	*F* (df)	p-value	η_p^2
Task HR	1.25 (4)	0.30 n.s.	0.05
Task LF-HRV	0.29 (4)	0.89 n.s.	0.01
Task HF-HRV	0.67 (4)	0.61 n.s.	0.03
Task HRV_a	1.02 (2.84)	0.39 n.s.	0.04
Recovery HR	0.90 (4)	0.47 n.s.	0.04
Recovery LF-HRV	1.27 (4)	0.29 n.s.	0.05
Recovery HF-HRV	0.66 (4)	0.62 n.s.	0.03
Recovery HRV	1.30 (4)	0.28 n.s.	0.05

* weakly significant; ** significant; *** highly significant; n.s. not significant
η_p^2<0.04= negligible; η_p^2≥0.04= small; p η_p^2≥0.25= moderate; η_p^2≥0.64= large

The results indicate that the differences in the testes parameters were non-significant (all p>0.05) across the five conditions during stress and recovery periods with negligible and very small effect sizes. Hence, no further analysis was conducted. LF/HF and BVA measures were analysed using Freidman's ANOVA test as indicated in Table A3-15.

Table A3-15. Friedman's ANOVA test for self-reported stress and PANAS

Parameter	Conditions	Mean rank	χ^2 (df=4)	*p*-value

Task LF/HF	30%	3.24	1.72	0.79 n.s.
	20%W	2.78		
	20%N	3.20		
	10%W	2.92		
	10%N	2.86		
Task BVA	30%	2.92	3.74	0.44 n.s.
	20%W	2.86		
	20%N	2.80		
	10%W	2.88		
	10%N	3.54		
Recovery LF/HF	30%	2.44	10.72	0.03 *
	20%W	3.40		
	20%N	2.76		
	10%W	2.72		
	10%N	3.68		
Recovery BVA	30%	3.16	1.82	0.77 n.s.
	20%W	3.16		
	20%N	2.64		
	10%W	3.04		
	10%N	3.00		

* weakly significant; ** significant; *** highly significant; n.s. not significant

The results indicate that only LF/HF during recovery was significant across the different conditions ($p<0.05$), accordingly, pairwise comparisons using Wilcoxon signed-rank test were conducted to explore the magnitude of differences. Table A3-16 reports the median (M_{dn}), the interquartile range (IQR), the associated significance (*p*-value), the (positive) and (negative) ranks, the ties, and the calculated effect sizes (*r*).

Table A3-16. Wilcoxon signed-rank tests and effect sizes for subjective recovery parameters

Parameter	Conditions	M_{1dn} (IQR)	M_{2dn} (IQR)	*p*-value	Negative	Positive	Ties	z	*r*
LF/HF	30 vs. 20W	-0.09 (0.32)	0.11 (0.36)	0.09 n.s.	15	10	0	-1.71	-0.24
	30 vs. 20N	-0.09 (0.32)	0.02 (0.30)	0.28 n.s.	16	9	0	-1.09	-0.15
	30 vs. 10W	-0.09 (0.32)	-0.02 (0.29)	0.38 n.s.	15	10	0	-0.87	-0.12
	30 vs. 10N	-0.09 (0.32)	0.09 (0.28)	0.00*.	18	7	0	-2.57	-0.36
	20W vs. 20N	0.11 (0.36)	0.02 (0.30)	0.09 n.s.	8	17	0	-1.71	-0.24
	20W vs. 10W	0.11 (0.36)	-0.02 (0.29)	0.10 n.s.	8	17	0	-1.63	-0.23
	20W vs. 10N	0.11 (0.36)	0.09 (0.28)	0.80 n.s.	14	11	0	-0.26	-0.04
	20N vs. 10W	0.02 (0.30)	-0.02 (0.29)	0.72 n.s.	12	13	0	-0.36	-0.05
	20N vs. 10N	0.02 (0.30)	0.09 (0.28)	0.10 n.s.	18	7	0	-1.66	-0.23
	10W vs. 10N	-0.02 (0.29)	0.09 (0.28)	0.11 n.s.	17	8	0	-1.60	-0.23

* weakly significant; ** significant; *** highly significant; n.s. not significant
$r<0.20$ = negligible; $0.20\leq r<0.50$ = small; $0.50\leq r<0.80$ = moderate; $r\geq 0.80$ = large

The pairwise comparisons provide evidence that the differences in LF/HF collected during recovery in different conditions are not significant in all comparisons (all p>0.005), and weakly significant in 1 case out of 9. Detected effect sizes were negligible in 4 cases (r<0.2) and small in 6 cases out of 10 (0.20≤r<0.50). LF/HF was slightly lower for 30% compared to remaining conditions (0.20≤r<0.50) and as indicated by a higher number of negative ranks. LF/HF was slightly higher for 20%W compared to 20%N and 10%W (0.20≤r<0.50) and as indicated by the high number of positive ranks. LF/HF was slightly higher for 20%N compared to 10%W and 10%N (0.20≤r<0.50) and as indicated by the high number of negative ranks. The variations in LF/HF between 30% and 10%W, between 20%W and 10N, and between 20%N and 10%W were negligible (all r<0.2).

To summaries, the subjective evaluations for view perception from different WWRs indicated a considerable decrease in view quality as the window size was reduced from 30% to 20% WWRs and 10%WWRs (Table A3-9); hence, 30% WWR is subjectively preferred. Physiological responses indicated that view quality is similar across all conditions except for 10%N, which considerably affected recovery from stress as indicated by SCL and LF/HF measures. Accordingly, 30% is the optimized WWR for view perception to attain best view quality subjectively and objectively.

A3.2.6 Reported Simulator Sickness Symptoms

SSQ before and after using the experiment were collected using ordinal scale and analysed using the Wilcoxon signed-rank test. The significantly different before and after using the VR symptoms are indicated in Table A3-17. The other symptoms: ‘General Discomfort’, ‘Headache’, ‘Difficulty Focusing’, ‘Salvation Increasing’, ‘Sweating’, ‘Nausea’, ‘Dizziness’, ‘Eyes Open’, ‘Dizziness Eyes Closed’, ‘Vertigo’, ‘Stomach Awareness’, and ‘Burping’ were not significantly different (p>0.05) with small or negligible effect sizes.

Table A3-17. Results of the Wilcoxon signed-rank tests for responses to questions on simulator sickness questionnaire

Parameter	After (M_{dn})	Before (M_{dn})	p-value	Negative	Positive	Ties	z	Effect size r
Eyestrain	2	1	0.00***	17	0	8	-3.87	-0.55
Difficulty Focusing	1	1	0.01**	9	0	16	-2.76	-0.39
Difficulty Concentrating	1	1	0.01**	11	1	13	-2.81	-0.40
Blurred Vision	1	1	0.01**	9	1	15	-2.48	-0.35
Dizziness /Eyes Closed	1	1	0.00**	9	0	16	-2.88	-0.41

* weakly significant; ** significant; *** highly significant; n.s. not significant
r<0.20 = negligible; 0.20≤r<0.50 = small; 0.50≤r<0.80 = moderate; r≥0.80 = large

Table A3-17 indicates that significantly reported symptoms were denoted by small effect sizes and a high number of ties (tied ranks ≥13) for all symptoms (i.e., when the evaluations across both conditions were the same), except for reported levels of eye strain. However, before leaving the experiment setting, all participants have consent that any discomfort that was experienced during the VR trial has subdued as found in previous experiments [23, 25].

A3.2.7 Window Size Optimization for Energy and Lighting performance

In order to optimize window size under the different climatic conditions, building simulations were conducted under twelve scenarios with different WWRs (Figure A3-3), to be assessed in relation to view perception results. The building annual energy consumption was evaluated, in addition to the annual percentage of working hours with illuminance levels that meet the different UDI criteria for insufficient (UDI<300), sufficient (300≤UDI<2000), and potential glare (UDI≥2000) under three climate conditions (Table A3-6). In Figure A3-8, energy consumption changing with WWRs is shown in stacked bars for cooling (grey), heating (orange), and artificial lighting energy (blue). The three curves indicate the values of different UDI thresholds that vary with WWRs simulated in the middle of the room.

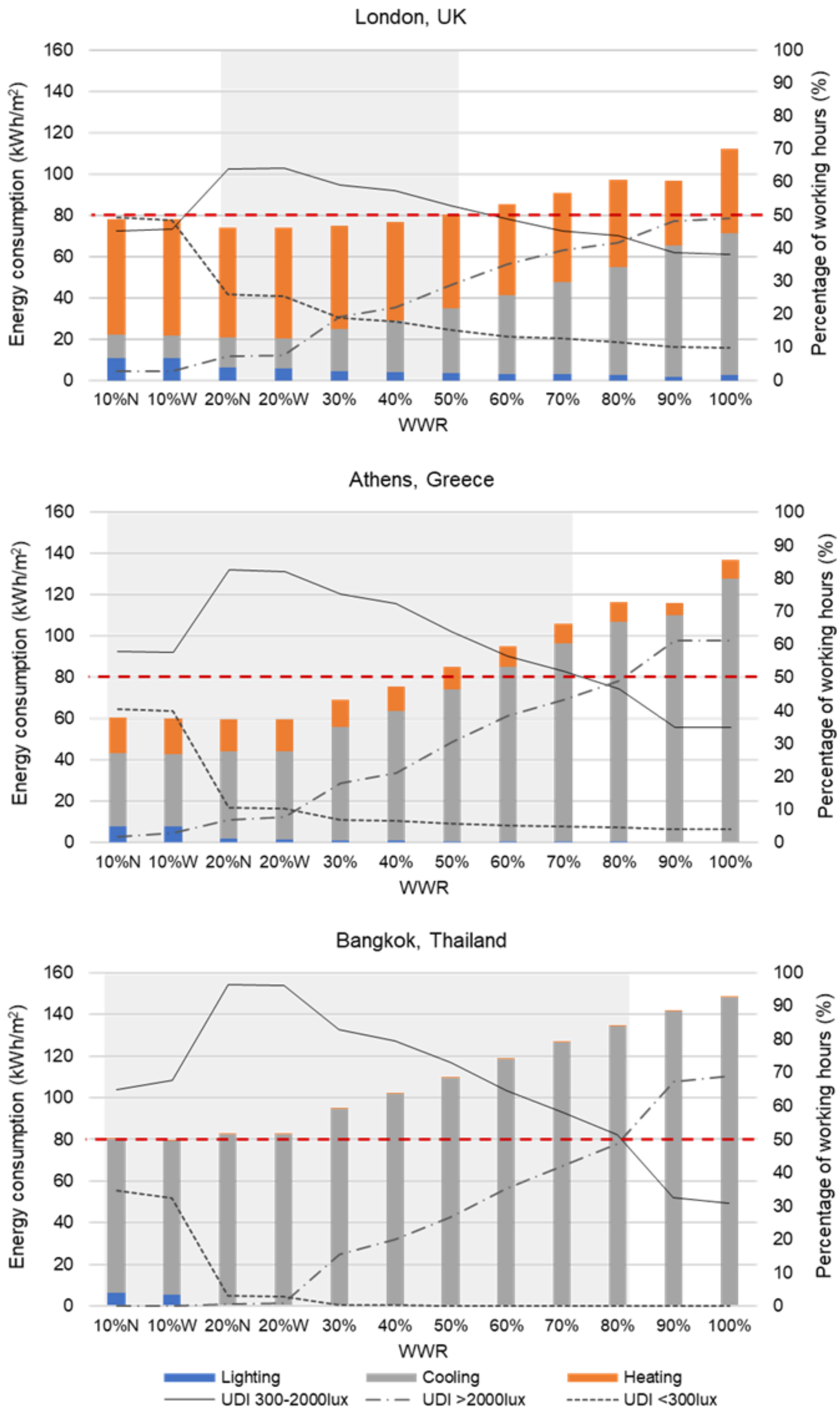

Figure A3-8. Building annual energy consumption and lighting performance for different window to wall ratios under different climate conditions

The energy consumption trends indicate that in all three climates, increasing the WWR become counterproductive providing larger areas for heat transfer, thus, requiring more cooling demands and lower lighting and heating demands. For UDI requirements, as the latitude decreases, a wider range of WWR can provide sufficient illuminance levels ($UDI_{300\text{-}2000}$) for 50% of working hours. Additionally, increasing WWR results in more glare potential hours and fewer hours with insufficient lighting. Normalized values of energy consumption (from 0 to 100) were used according to Percent of Maximum Possible (POMP) scoring [81] (Equation A3.1) for simplified energy consumption assessment [4]. In the equation, the x represents the annual energy consumption calculated for a certain WWR and minimum and maximum are the minimum and maximum energy consumption simulated across all WWR.

$$\mathrm{POMP} = \frac{\mathrm{x-min}}{\mathrm{max-min}} \times 100 \qquad \text{Equation (A3.1)}$$

Normalized energy consumption values along with percentage hours with different illuminance thresholds are detailed in Table A3-18. For the following discussion, energy, or lighting values with differences lower than 5% are considered to have similar performance.

Table A3-18. Energy and lighting performance for different WWRs

Climate	Parameter	10N	10W	20N	20W	30	40	50	60	70	80	90	100
London	Energy	11.4	11.2	0.2	0*	2.7	7.5	17.4	29.5	43.9	60.6	59.2	100
	$UDI_{<300}$ lux	50.2	49.6	26.8	26.2	19.8	18.7	16.3	14.2	13.5	12.5	11.2	10.9
	$UDI_{300\text{-}2000}$ lux	46.1	46.7	64.8	65.3*	60.1	58.3	53.9	49.7	46.2	44.8	39.6	39.1
	$UDI_{>2000}$ lux	3.7	3.7	8.4	8.5	20.1	23.0	29.8	36.1	40.3	42.7	49.2	50.0
Athens	Energy	1.6	1.0	0.1	0*	12.5	21.0	33.2	46.3	60.1	73.5	73.4	100
	$UDI_{<300}$ lux	40.4	39.8	10.5	10.2	7.0	6.4	5.8	5.2	4.8	4.5	4.1	4.0*
	$UDI_{300\text{-}2000}$ lux	57.9	57.6	82.7*	82.1	75.1	72.4	63.8	56.4	51.9	46.5	34.9	34.9
	$UDI_{>2000}$ lux	1.7*	2.6	6.8	7.7	17.9	21.2	30.4	38.4	43.3	49.0	61.0	61.1

Bangkok	Energy	1.4	0*	4.1	4.0	21.5	32.3	43.2	56.8	68.6	89.7	79.4	100
	$UDI_{<300}$ lux	34.6	32.3	3.1	2.9	0.4	0.3	0.1	0.1	0.0*	0.0*	0.0*	0.0*
	$UDI_{300-2000}$ lux	65.4	67.7	96.4*	96.2	83.0	79.6	73.1	64.6	58.1	51.3	32.6	30.9
	$UDI_{>2000}$ lux	0.0	0.0	0.5	0.9	15.6	20.1	26.8	35.3	41.9	48.7	67.4	69.1

* window sizes with optimized performance for each evaluating parameter

As indicated in Figure A3-8, for London's temperate climate, smaller WWR was found to be increasing heating loads due to the decrease in passive solar heating, while cooling loads become the main source of energy consumption as the WWR increases. For example, in 10%N case, the lighting, cooling, and heating loads represent 13.73%, 14.36%, and 71.91 % of total energy consumption, respectively; while in 100% WWR case, 2.08%, 61.33%, and 36.58% of total energy consumption are due to lighting, cooling, and heating loads, respectively. Total energy consumption for cooling, heating, and lighting was found to be lowest with 20%W case, and slightly lower than 20%N and 30 % cases (<5%); hence, a range between 20% and 30% WWR is recommended for best energy consumption. For daylight performance, sufficient illuminance hours were found with WWRs ranging from 20% to 50% with maximum hours of sufficient lighting resulting when 20% WWRs are applied (with over 60% sufficiently illuminated hours). Hence, for daylight and energy performance, a 20% WWR is the optimised choice.

Similar to London's case, under the Mediterranean climate of Athens, smaller WWR found to be increasing heating loads due to the decrease in passive solar heating, while cooling loads become the main source of energy consumption as the WWR increases. For example, in 10%N case, the lighting, cooling, and heating loads represent 13.00%, 58.25%, and 28.74% of total energy consumption, respectively; while in 100% WWR, 0.24%, 93.34%, and 6.41% of total energy consumption are due to lighting, cooling, and heating loads, respectively. The lowest energy consumption in Athens was found when 20% WWRs were applied with slightly lower values found for 10% WWRs (<5%); hence, a range between 10% and 20% WWR is the optimized size for energy consumption. For daylight performance, wider WWR ranges than those found in the UK case were able to provide the desirable lighting ($UDI_{300-2000}$). The 50% of working hours threshold was attained with WWR ranging from 10% to 70%, and the best daylight performance was found with the 20% WWR with almost 80% of working hours falling within the sufficient illuminance range. Hence, the 20% WWRs is the optimized size for both energy and daylight performance.

For Bangkok tropical climate, the results showed a higher total energy use due to a greater cooling energy demand in all simulated WWRs. Unlike the previous climates, heating loads are almost not required for Bangkok climate. The cooling loads in 10%N case were found to equal 91.44% compared to 99.94% in 100% WWR, indicating the high cooling demand for this climate. Lowest energy consumption for the tropical climate was found with 10% WWRs; however, slightly lower than 20% WWRs (<5%); hence, a range between 10% and 20%WWR is the optimized size for energy consumption. For lighting performance, wider WWR ranges than those found in London and Athens cases were able to provide the desirable lighting ($UDI_{300-2000}$). The 50% of working hours threshold was attained with WWR ranging from 10% to 80%, and the best daylight performance was found with the 20% WWR with over 90% of working hours falling within the desirable sufficient range. Since the 20% WWRs energy performance was slightly higher than the 10% WWRs, it can be concluded that 20%WWR condition is the optimized size for both energy and daylight performance.

A3.3 Discussion

This study was conducted to evaluate the window size impact on window performance using a threefold criterion: view perception, energy consumption, and daylight performance.

The results of this study indicate substantial differences in the subjective and physiological measures given to perceived view quality observed from different window sizes in a virtual environment replicating a daylit office room. Subjective and physiological measures revealed higher view quality with larger window size which support subjective preferences of larger windows [17-19]. All subjective evaluation parameters were significantly higher (or close to significant 0.05) for the 30% WWR compared to 20% and 10% WWRs with moderate and substantial magnitudes, respectively. The location of view quality on valance/arousal was also considerable as it showed that change in view size resulted in a shift in observers' affect along with the excitement–dull axis, providing a less stimulating working environment as the window size becomes smaller [82].

Subjective recovery from the stress indicators (ΔStress, ΔPA, and ΔNA) showed improved values when participants observed the 30% condition as donated by the effect sizes and by the large numbers of positive ranks in PA comparisons, and large numbers of negative ranks in stress and NA results (Table A3-10). Hence, with similar content, larger windows increase the perceived view quality and restorativeness as indicated by subjective recovery and by SCL and LF/HF physiological measures (Table A3-13 and Table A3-15). The results further confirmed that recommended 20% WWR in BREEAM standards for rooms with depth ≤8 m might not guarantee an adequate view for occupants.

For all view perception parameters, the differences were slightly higher between 30% and 20%N compared to those between 30% and 20%W. The differences were negligible between 20% WWRs for all view perception parameters except for “Size” as participants preferred the 20%W more. The location of view quality on valance/arousal was also close for these two conditions and the differences in SCL and LF/HF results were small; indicating that participants perceived the views similarly in these two conditions.

Nevertheless, differences between 30% and 10%N for all parameters were larger than those found between 30% and 10%W, this was also confirmed by SCL and LF/HF results, and by location of view quality on arousal/valence model. The differences in view quality perception between 10%N and 10%W were larger than those found between the 20% WWRs as participants preferred the view provided by the 10%W. These results suggest that the window layout (i.e., aspect ratio) has affected the perceived view quality (i.e., lower perceived view quality reported with narrower windows or small aspect ratio).

In previous research [19] with a 20% WWR, observers preferred wider window layout (larger aspect ratio) when the view content is a built environment, while narrower windows were more acceptable when the view consisted of distant city landscape (i.e., with sky and ground components). This was further confirmed for built view by this study results for 20% and 10% WWRs, which underlines the need for window size recommendations to consider the aspect ratio (or dimensions) instead of only reporting WWR, as exaggerated proportion might affect restorativeness of the view. Moreover, initial responses to view from 30% and 20%W WWR showed lower

HRV_a indicating increased mental work [50], which might indicate more cognitive engagement with the observed view.

To discuss view perception results in relation to energy and lighting performance, a graphical optimization method was used as indicated in Figure A3-9. A vertical grey shaded area on the graph indicates the WWR range that attains the sufficient lighting performance threshold (i.e., 50% of working hours falls under sufficient illuminance criterion ($300 \leq UDI < 2000$). The lowest energy consumption is indicated by stacked bars with the lowest value, while view perception evaluations are indicated by green double-arrow line for subjective responses and a yellow one for physiological responses.

The subjective evaluations for view perception from different WWRs indicated a considerable decrease in view quality as the window size was reduced from 30% to 20% WWRs (Table A3-9); hence, 30% WWR is subjectively preferred. Physiological responses indicated that view quality is similar across all conditions except for 10%N, which considerably affected recovery from stress as indicated by SCL and LF/HF measures. Accordingly, 30% is the optimized WWR for view perception to attain best view quality subjectively and objectively. However, when assessed against WWRs optimized for energy and lighting performance, the results were not always compatible.

Figure A3-9. Building annual energy consumption, lighting performance, and view perception for different window to wall ratios under different climate conditions

For London, Athens, and Bangkok climates, a 20% WWR was the optimized size for daylight and energy performance. Nevertheless, when compared to subjective and objective (physiological) results on view quality perception, the 20% WWRs did not satisfy subjective view quality; hence, a 30% is the optimized WWR for view, energy, and daylight performance. Although in London the 30% WWR produces slightly higher energy consumption and guarantees sufficient illuminance levels for work (attains the 50% threshold), it increases the glare potential hours by 11.6%. Although the lighting performance of the 30% WWR is within is the sufficient range, the energy consumption and the glare potential hours (above UDI_{2000}) increase by 12.5% and 17.5%, respectively in Athens and by 10.2% and 14.7% for Bangkok case, respectively.

The evaluation of WWRs for energy and lighting results revealed variations in the optimized WWR for each individual criterion and indicated that the optimization for only one criterion might negatively influence the remaining. Although increasing WWR might increase view quality provided, for the selected climates with south orienting window, this found to be increasing the total energy consumption and decreasing the percentage of working hours with useful illuminance levels as more glare hours will occur. Unlike energy consumption, daylight performance was slightly affected by the aspect ratio, and further research on lighting performance using other metrics of visual comfort (uniformity) might reveal different results.

Therefore, in order to optimize the WWR for energy, daylight, and view perception, a careful design process at early stages that accounts for this issue is needed. I.e., improve energy and daylight performance for larger windows by utilizing different window design solutions, such as shading devices and glazing types; yet, without compromising the view quality (restorativeness), as it might affect participants health and wellbeing.

When comparing the impact of the viewing position on view perception results in a former study [123] with the current one, locating the participants closer to the window with a 20% WWR window substantially improved the perceived quality of the view (restorativeness), as more informative parts of the view were visible (i.e., sky) due to the parallax effect. This feature might be useful for energy consumption purposes (i.e., a smaller window that has a high-quality view could save more energy); however, the glare issue will increase and should be mitigated.

Although the investigated WWRs for view perception were limited, the method used in this study could be applied to assess different energy and daylight solutions impact on view quality perception to provide deeper insight into this matter. Another limitation of this study is the reported simulator symptoms by the participants following the use of VR technology. Although these symptoms are usually associated with the application of VR environments [16], they are generally minor and short-lived [83], which is consistent with the findings of the previous experiments.

Another limitation of this work is the usage of single room profile (i.e., same air change rate and thermal transmittance) for all simulated climates. Although this was conducted to minimise variation in simulation across the different climates, future studies with local standards and building envelope practice should be conducted using similar approach to the one used in this paper to actually reflect the window performance for each climate.

A3.4 Conclusion

In this study, a novel comprehensive method to assess window performance for view perception, energy, and daylight was presented. A 360^o virtual environments were used to represent five different window sizes showing their corresponding views seen in a daylit office. Several subjective and physiological measures were used to quantify the differences in view perception based on parameters of restorativeness from stress across the different conditions. The results were assessed in relation to energy consumption and daylight performance simulated for different window sizes. The designed methodology identified statistically significant differences in view perception in the measures that were evaluated. The main findings of this study are:

- The window size and layout have a significant influence on view quality measured through the use of subjective and physiological parameters, whereby increased view quality was reported the largest the window has become within the virtual environment.

- Increased view quality was found when participants observed view from larger WWR in the VR setting. When comparing the differences in subjective evaluations given between the 30% and 10%N WWR conditions: the self-reported levels of “fascination” and “being away” increased by 50% and 55%; “excitement” and “pleasantness” increased by 52% and 50%; and satisfaction with “view content”, “size”, and perceived “interest” and “complexity” increased by 51%, 61%, 49% and 40%, respectively.

- Decreases in physiological stress levels were found when participants observed the larger views in the VR setting. Stress levels during recovery showed a significant reduction in SC and LF/HF when comparing the measurements collected at 30% and 10%N cases.

- The change in aspect ratio also affected view quality reported between different window sizes. Participants reported increased view quality from 10%W compared to 10%N WWR: the self-reported levels of "fascination" and "being away" increased by 27% and 37%; "excitement" and "pleasantness" increased by 27% and 31%; and satisfaction with "view content" and perceived "interest" increased by 31% and 40%, respectively. Although having similar "size", satisfaction with size increased by 45% for the wider layout in 10%W, hence, it is suggested that exaggerated proportion has a major impact on view quality (restorativeness) and further investigation is encouraged.

- Recommended WWRs given by standards might not guarantee the view benefits (restorativeness). Alternatively, the windows' physical dimensions in relation to the view content should be considered as wider windows were prefered over narrower ones in this study.

- Energy consumption, daylight performance, and view perception showed different optimized window sizes for a south oriented window under certain climates. Increasing WWR from 20% to 30% to attain enhanced view restorativness in Athens for example, would increase energy consumption and glare potential hours by 12.5% and 17.5%, respectively. Hence, an early design optimization process is required to provide improved windows performance for healthier working environments.

This study was conducted with one view content (building) observed from a small range of WWR (10% to 30%). Further studies with a wider range of WWR should be conducted to assess whether there is a limit to WWR enlargement as other psychological aspects might impact the occupant's preference of view size (e.g., privacy and control). Similar studies with variety of view contents are needed to assess the impact of view content on window size preference as smaller windows showed enhanced performance for energy and lighting. This could lead to a reference guide for window size preferences in relation to the neighbouring context of new constructed buildings, and related energy and lighting performance could be easily assessed correspondingly.

As indicated by effect sizes of physiological measures for observer location [25] and window size, proximity to window influenced the view quality (restorativeness) more due to parallax effect. In other words, for the same window size, placing occupants closer to the window will increase the restorativeness of the view (if the sky component becomes visible) more than increasing the size of the window to 30% from the same observer location. Hence, the interaction between different view parameters (observer location, size, and content, etc.) will give further insight on view perception and might provide more variety for energy and lighting performance.

It should be noted that while the results obtained in this study are applicable in UK case, it might not be the case for the other two climates as using the thermal transmittance and ventilation standards recommended for each climate may reveal different results. In addition, view perception (i.e., view size) might be different across different regions and climates when other social considerations are considered. Nonetheless, the results obtained in this study are suggestive and encouraging for using the same method to enhance existing and future window systems to be more occupant oriented.

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Declaration of Interest

None.

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Appendix A3-1

Table A3-1.1 List of the view perception questionnaire items used during the experiment

Parameter		Adopted to view Questions	Bipolar descriptors	Ref.
View restorative ability Adopted from Perceived Restorativeness Scale	Fascination	This view is fascinating My attention is drawn to many interesting things in this view	“Not at all” – “Very much”	[88, 165-168]
	Being away	Looking at this view would give me a break from the work routine		
		Looking at this view helps me to relax my focus on getting things done		
View content		I like the view provided by the window		[88, 165-167]
View size		How satisfied are you with the amount of view in this space?		[15, 18, 19, 48]
View valance/arousal		How pleasant is the view? How exciting is the view?		[18, 48, 97]
View interest		How interesting is this view? How complex is this view?		
View complexity		The view provided by the window has variety of elements		[169]

Table A3-1.2 Experiment detailed procedure and duration

Time progress in minutes	Activity	Duration in minutes
0-5	Welcome and introduction, sign the consent form and complete Pre-test questionnaires (demographic and SSQ)	5
5-8	Demonstration of the experiment in the test room to make sure subjects understand the procedures and familiarise with VR	3
8-10	Connect SC and HR sensors to non-dominant hand and start physiological recordings	2
10-13	Participants wear VR and answer questionnaire (stress and PANAS)	3
13-17	Take baseline measurements	4
17-28	View the first condition and answer questionnaire (view perception), complete the Stroop test, and then look at window view to recover and answer the questionnaire (stress and PANAS)	11
28-35	Participants rest outside the experiment room and experimenter prepare for second condition	7
35-39	Take baseline measurements	4
39-50	View the second condition and answer questionnaire (view perception), complete Stroop test, and then look at window view to recover and answer the questionnaire (stress and PANAS)	11

52-59	Participants rest outside the experiment room and experimenter prepare for next condition	7
59-64	Take baseline measurements	4
64-75	View the third condition and answer questionnaire (view perception), complete Stroop test, and then look at window view to recover and answer the questionnaire (stress and PANAS)	11
75-82	Participants rest outside the experiment room and experimenter prepare for next condition	7
82-86	Take baseline measurements	4
86-97	View the fourth condition and answer questionnaire (view perception), complete Stroop test, and then look at window view to recover and answer the questionnaire (stress and PANAS)	11
97-104	Participants rest outside the experiment room and experimenter prepare for next condition	7
104-108	Take baseline measurements	4
108-119	View the fifth condition and answer questionnaire (view perception), complete Stroop test, and then look at window view to recover and answer the questionnaire (stress and PANAS)	11
119-123	The participants sign post-study consent form and SSQ questionnaire	4
123-125	End of experiment. The participant will be thanked for their time, led to the door and told they are free to leave	2

Appendix A3-2

A Holistic Approach to Assess Window Performance: Optimizing Window Size for View Perception, Energy, and Daylight

Participant Information Sheet

Project Title: Evaluating Visual Performance in Virtual Office Space Using Physiological Measures

Researcher: Fedaa Abd-Alhamid [laxfa10@nottingham.ac.uk]

Supervisor(s): Dr. Yupeng Wu [Yueng.Wu@nottingham.ac.uk], Dr. John Calautit, and Dr. Peter Rutherford

Advisor: DR. Michael Kent

Thank you for agreeing to take part in this research study about evaluating visual performance in virtual office environment. Before you begin, we would like you to understand why the research is being done and what it involves for you.

The Study

The purpose of this study is to evaluate how virtual reality could be used to assess visual task performance and its related stress using physiological signals as an objective measure. You have been invited because you meet the criteria the researchers of this project are looking for participants:

i. Between the age of 18 and 45.
ii. Speak fluent English.
iii. Willing to view a virtual reality environment using head mounted display.
iv. Who do not have any neurological disorders (eg. epilepsy).
v. Who do not suffer from migraines, motion sickness, dizziness or sleep disorders.
vi. Who are not visually impaired (eg. glaucoma).
vii. Who do not have colour vision defects (eg. colour blindness).
viii. Willing not to overwork or intake caffeine for the 8 hours prior to the study.
ix. Willing not to intake alcohol for the 24 hours prior to the study.

We would like to remind you that this study is optional, and it is up to you to decide whether or not to take part. If you do decide to take part, you will be asked to sign a consent form. Following this, you will be asked to fill out an initial questionnaire to collect some basic information about yourself including demographic information (age, gender etc.) and simulator sickness questionnaire.

Afterward, the researcher will lead you into a test room where heart rate sensor will be connected to your middle finger and two skin conductance sensors will be connected to your index and ring fingers. All sensors will be connected to your left hand. The recorded signals will be sent to a computer to record the results. This procedure is widely accepted to have no risk and to be a non-invasive technique to record physiological response.

Then you will be exposed to five different virtual environments and asked to complete a simple task during each. This will include stating the colours of words on a chart on the wall. Also, you will be answering questions about the virtual environment. After each test environment you will be asked to have a seven-minute break before taking the next test environment.

Will the research be of any personal benefit to me?

You are voluntarily participating in this study. We cannot promise the study will help you personally, but the information we get from this study may help gain a better insight into better architectural space requirements for decreased stress levels within office environments.

Are there any possible disadvantages or risks in taking part?

When using virtual reality, there is a risk that you might experience “simulator sickness”. It involves symptoms similar to those of motion-induced sickness, although simulator sickness tends to be less severe and to be of lower incidence. People who suffer from epilepsy, migraines, motion sickness, dizziness, sleep disorders or blurred vision are more likely to experience adverse effects, so please do not take part in the study if you suffer from any of these conditions. If you experience any symptoms during the session, or any other discomfort, please alert the investigator immediately, or you can simply remove the headset yourself, like you would a pair of googles.

What will happen to the information I provide?

We will follow ethical and legal practice and all information will be handled in confidence. The data collected for the study will be looked at and stored by authorised persons from the University of Nottingham who are organising the research. They may also be looked at by authorised people from regulatory organisations to check that the study is being carried out correctly. All will have a duty of confidentiality to you as a research participant and we will do our best to meet this duty.

What if there is a problem?

If you have any queries or complaints, please contact the student’s supervisor/ investigator in the first instance.

What if I have other questions?

If you have any questions or concerns, please don’t hesitate to ask. The researcher can be contacted before and after your participation at the email address above.

Participant Consent Form

Project Title: Evaluating Visual Performance in Virtual Office Space Using Physiological Measures

Researcher: Fedaa Abd-Alhamid [laxfa10@nottingham.ac.uk]

Supervisor(s): Dr. Yupeng Wu [Yueng.Wu@nottingham.ac.uk], Dr. John Calautit, and Dr. Peter Rutherford

Advisor: DR. Michael Kent

I the undersigned as research participant confirmed that (please sign your initials as appropriate)

☐ 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 do not suffer from any of the following: epilepsy, migraines, motion sickness, dizziness, sleep disorders or blurred vision.

☐ 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, and that digital data will be stored only on a password-protected computer and on a secure server. Only researcher 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 supervisor and the supervisor 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 ……………………………..… Date …………………………………

Signed ………………………………………………………… (Researcher)

Print name ………………………….…… Date ………………………………….

Post Study Participant Consent Form

Project Title: Evaluating Visual Performance in Virtual Office Space Using Physiological Measures

Researcher: Fedaa Abd-Alhamid [laxfa10@nottingham.ac.uk]

Supervisor(s): Dr. Yupeng Wu [Yueng.Wu@nottingham.ac.uk], Dr. John Calautit, and Dr. Peter Rutherford

Advisor: DR. Michael Kent

I the undersigned as research participant confirmed that (please sign your initials as appropriate)

- ☐ Any feelings of discomfort I may have felt during the trials have subsided.
- ☐ I have been advised to wait for approximately 30 minutes between completing the simulator trial and driving

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

Print name ……………………………...… Date …………………………………

Signed ………………………………………………………… (Researcher)

Print name ……………………………..…… Date ………………………………….

Contact details:

Researcher: Fedaa Abd-Alhamid [laxfa10@nottingham.ac.uk]

Supervisor: Dr. Yupeng Wu [Yueng.Wu@nottingham.ac.uk]

Pre-Test Subject 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_________________ □prefer not to say

5. If yes, are you using glasses or contact lenses to correct any eye conditions?

□ Yes □ No □Prefer not to say

6. What is your ethnic background?

□ White □ Mixed / Multiple ethnic groups □ Asian

□ Black / African / Caribbean / Black British □ Other ethnic group ______
□ Prefer not to say

7. What is current state of health? □ Ill □ Not too bad □Good □Prefer not to say
8. 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.

____
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Appendix A4

Paper 4: A |Refined Methodology to Quantify View Perception

(This part is written in a paper format to be submitted for journal publication)

A Refined Methodology to Quantify View Perception

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Abstract

Indoor environmental quality has a major impact on occupants' perceptions of their immediate environment. Views from windows are key factors that affect the indoor environmental quality perception by providing connectivity to the outdoor environment and restorativeness from stress which affects occupants comfort, productivity, health, and well-being. Nevertheless, views from windows are usually overlooked when buildings envelope performance is evaluated. The absence of a robust methodology to assess view perception (i.e., to quantify view quality) and the difficulty to conduct experiments in continuously changing daylit environments might be the reasons for not considering the "view" factor in similar research. This chapter provides guidance to assess view perception based on reliability tests and correlation analyses of subjective and objective data, respectively, collected from two studies on view perception. This guidance offers a refined method to assess view perception in future studies for more occupant-oriented evaluations of building envelope and window design.

Keywords: Correlation analysis, Reliability analysis, Subjective responses, Physiological responses, Window-view quality, Virtual reality.

A4.1 Introduction

Indoor environmental quality has a major impact on occupants' perceptions of their immediate environment which may affect their comfort, productivity, health, and well-being. Continuing research is being conducted to develop advanced technologies to optimize the building envelop performance that provides the best energy performance while ensuring both visual and thermal comfort of occupants. Nevertheless, the impact of such technologies on occupants' connectivity to the outdoor environment is usually not considered in similar research.

Views provided by windows are key factors that affect the indoor environmental quality perception [1, 2] and provide connectivity to the outdoor environment. High-quality views positively impact the occupants overall psychological and physiological comfort and increase satisfaction with the working environment [3]. Hence, assessing view perception besides visual and thermal comfort and energy performance parameters will further enhance the buildings envelope performance and provide an inclusive approach for new windows' technologies assessment.

The difficulty to conduct view perception experiments in continuously changing daylit environment [4, 5] and the difficulty to investigate the different designs alternatives impact on view perception might be the reasons for not considering the view perception when new technologies are being developed. The inadequate methods available to quantify view quality might be another reason. Hence, a refined methodology that accounts for those reasons is required to facilitate the investigations on view perception.

In a previous study (appendix A1), a physical-based virtual method that replicates the luminous conditions of a real environment was developed and validated to be used as a representation method for different experimental visual conditions. For view quality assessment, a comprehensive method of subjective and objective (physiological) evaluations was developed and used to evaluate the variations in view perception resulted by changing the observer's location within the room (appendix A2), and by changing window size (appendix A3).

In this study, the reliability of the constructed subjective questionnaire on view perception was tested and discussed. Furthermore, the results obtained in the two studies suggested a similar trend in both subjective and objective evaluations; hence, a correlation analysis between subjective and objective (physiological) data collected in previous studies presented in appendices A2 and A3 was conducted. This was considered to further validate the physiological evaluations as objective measures to quantify the view, to provide a guide on what are the best signals to use for each part of the research, and to evaluate the strength of association between subjective and objective responses on view perception. Based on the analysis, recommendations are presented for a more refined methodology that can be used to conduct further studies on view perception.

A4.2 Methodology

A4.2.1 Experimental Setting and Participants

The data used for the analysis in this study was collected while participants are immersed in a virtual environment in two separate investigations. In both experiments, the test room was located in the Energy Technologies Building (University of Nottingham, UK). In both experiments, a physically-based virtual reality (VR) environments that replicate the test-room physical and photometric conditions were used to reproduce different experimental conditions (i.e., change in window view provided). The VR environments were generated using calibrated HDRI images with point luminous measurements and tone-mapped with 2.2 gamma and key value of 0.01 which created similar contrast values to the real environment [6]. The detailed methodology used to generate the VR environments was developed and validated in a previous study [7]. The final VR environments used in both experiments are illustrated in Figure A4-1.

Because the view has a profound influence on both psychological (i.e., subjective ratings that appraise the visual content) and physiological (i.e., levels of stress) when a window is observed by an occupant, a multi-criteria approach that utilises both types of measures was adopted to quantify the differences in view perception. Subjective evaluations included questions on view perception and reported stress and affects. Objective responses were collected using physiological indicators including skin conductance (SC), heart rate (HR), and heart rate variability (HRV) [8, 9] to measure stress levels throughout the experiment duration to quantify view perception by its restorativeness.

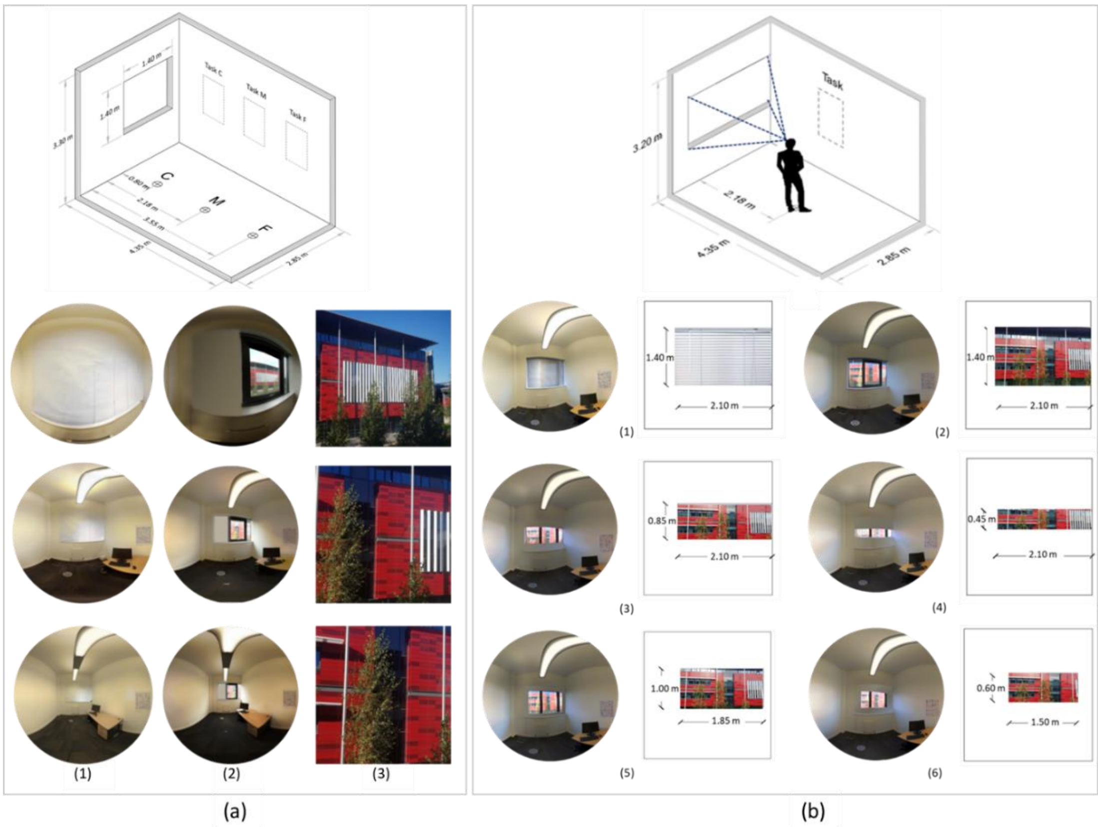

Figure A4-1. Image (a): The test room dimensions and the three observing locations along with (1) their corresponding windowless baseline environments; (2) the three environments with view indicating the view size in the visual field; (3) the corresponding view content for each location. Image (b): a) The test room dimensions and observer location along with (1) the windowless baseline environment; (2) the 30% WWR; (3) the 20%N WWR; (4) the 10%N WWR; (5) the 20%W WWR; (4) the 10%N WWR.

In the first experiment about view perception resulted by changing the observer's location within the room, subjective data was collected from a total of 32 subjects; 23 males and 9 females with a mean age of 28 years (SD= 6.08), while for the physiological data, the final sample size was 28 participants: 22 males and 6 females with a mean age of 29 years (SD= 6.24). In the second experiment about view perception resulted by changing window size, both subjective and physiological data were collected from 25 participants: 14 males and 11 females with a mean age of 27 years (SD= 5.26).

A4.2.2 VR as Visual Stimuli Representation Method

In both experiments, physical-based virtual environments that replicate the luminous conditions of real environments were used. Real and virtual environments were assessed using subjective responses (questions on luminous environment appearance, quality, and high order impressions) and objective responses (i.e., contrast-sensitivity and colour-discrimination tasks). The detailed methodology that could be followed to create validated virtual environments is described in chapter 3 [7]. The aspects of the luminous environment that were validated (i.e., replicated) in the virtual environment are illustrated in Table A4-1.

Table A4-1. The validated parameters on luminous environment perception in VR

Perception parameter		Validation method		Notes
		Subjectively	Objectively	
Visual quality of the luminous environment	Details	x		Limited resolution of VR
	Contrast	x	√	Based on task performance
	Colourfulness	x	√	Based on task performance/ except for fine details
	Colours vividness	√		Replicated with negligible or small differences
The appearance of the luminous environment	Colour temperature	√		
	Brightness	√		
	Distribution	√		
High-order Impressions of the luminous environment	Pleasantness	√		
	Interest	√		
	Complexity	√		
	Excitement	√		
	Spaciousness	√		

The developed methodology was validated for a wide variety of parameters including visual quality of the luminous environment evaluated by its contrast, colourfulness, and colours vividness; the appearance of the luminous environment evaluated by the lighting colour temperature, brightness, and distribution; and high-order impressions of the luminous environment comprising pleasantness, interest, complexity, excitement, and spaciousness. These parameters were either validated subjectively or objectively using contrast and colour naming task performance except for the details' parameter (i.e., participants rated the level of details in VR lower than those in the real environment) which was limited by the resolution of the VR head-mounted display [7]. Nevertheless, participants were able to give correct responses when performing visual tasks presented in the virtual environment, and since the visual information is acquired from the scene based on its shape, contrast, and colour [10], and regardless the lower resolutions as those offered by VR, the overall appearance of the scene can still be correctly perceived as shown for different tested parameters.

The developed method can produce realistic visual contrast and colour properties within a certain degree [59] and is capable of providing a much higher degree of experimental control over parameters that would vary in buildings (e.g. temperature, noise, daylight, etc.), which is one of the main challenges in experimental studies using windows [20, 61]. The illumination levels can also be maintained in VR settings across different experimental conditions, which can affect the investigated visual stimuli perception if left uncontrolled [20]. Additionally, the method offers the flexibility of apparatus allocation allowing the reproducibility of consistent conductions of the experiments [13], and allows, the rapid change of visual stimuli in VR environment which reduces the time needed to perform the experiment, hence, provides more time for the analysis. Also, the experimenter can replicate the same experimental setup with a wide range of visual stimuli and the same surrounding environmental factors.

However, the provided luminance levels in are limited with similar displays (~216 cd/m^2) [11] and approximately equals 118 cd/m^2 [7], which restrict the use of VR when considering the evaluation of glare caused by high luminance values as HDRI cannot be displayed directly in the VR; and its dynamic range must be compressed to the low dynamic range of the display.

A4.2.3 Subjective Evaluations of View Quality

Two groups of subjective evaluations were used to evaluate view perception: view perception questionnaire and stress-related questionnaire. The view perception questionnaire evaluated view restorative ability, view content, view size, view valance/arousal, visual interest, and complexity. All questionnaire items were measured on a continuous scale ranging from "Not at all" (= 0) to "Very much" (= 10). Similar questionnaires were used in both experiments, with an additional question on the perceived complexity in the second experiment as indicated in Table A4-2. Stress was evaluated using self-reported stress question and PANAS questionnaire [12], which were performed during the baseline and recovery periods to assess view quality by its impact on subjective recovery. Questionnaires were answered verbally, and the answers were recorded using Dictaphone, which is more convenient when VR is used [4, 13]. The questions were randomised across the different conditions in both experiments to eliminate any bias in subjective responses [14]. The reliability of the designed questionnaire on view perception is discussed in the analysis section.

Table A4-2. List of the view perception questionnaire items used during the experiments

Parameter	Questionnaire item	Bipolar descriptors	Ref.

View restorative ability Adopted from Perceived Restorativeness Scale	Fascination	This view is fascinating. My attention is drawn to many interesting things in this view.		[15-19]
	Being away	Looking at this view would give me a break from the work routine.		
		Looking at this view helps me to relax my focus on getting things done.		
View content		I like the view provided by the window.		[15-18]
View size		How satisfied are you with the amount of view in this space?	"Not at all" – "Very much"	[4, 5, 20, 21]
View valance/arousal		How pleasant is the view? How exciting is the view?		[4, 13, 21]
View interest		How interesting is this view? How complex is this view?		
View complexity		The view from the window provides variety of elements*		[22]

*The additional question on view perceived complexity used in the second experiment

A4.2.4 Physiological Data Collection

The detailed physiological apparatus and data screening method were similar in both experiments as presented in previous appendices A2 and A3. A wide range of physiological measures was explored to test its appropriateness to be used as an objective tool to quantify view perception. The physiological markers were utilized to measure the view quality by collecting the data when the participants first observed the view as an initial response, and by comparing the data collected during baseline and recovery to assess view quality by its impact on physiological recovery.

In both experiments and upon arrival to test room, participants sat at the centre of the room on a rotatable chair with an armrest that was used to minimise hand-movement when the physiological measurements were recorded. All physiological recordings were collected while the participants are immersed in the VR setting. The selected physiological measures can continuously monitor nervous system activity in terms of stress and recovery [23-27]. Both SC and HR data were recorded using sensors connected to the Mind Media Nexus-10 MKII acquisition device and were sampled at 32 samples per second (SPS) rate.

During the experiments, the HR sensor was connected to the middle finger of the participants' left hand to sense the blood flow rate from which different measures of HRV– including low frequency (LF-HRV) (0.04 to 0.15 Hz), high frequency (HF-HRV) (0.15 to 0.4 Hz), low frequency to high frequency ratio (LF/HF), heart rate variability amplitude (HRV_a), and blood volume pulse (BVA) can also be acquired. The Ag-AgCL electrodes for the SC sensor were attached to the distal phalanx of the index and ring fingers of the participants' left hand to measure the sweat gland activity of participants regulated by the sympathetic nervous system, indicating states of elevated stress [8, 28]. A summary of the used physiological measures in both studies and their interpretations (when increase or decrease) in terms of emotional response and stress status are presented in Table A4-3.

Table A4-3. Physiological measures used in each experiment to assess view quality

Physiological measure	First expirement	Second expirement	Purpose of use	Interpretation	Ref.
SCR	√	√	Initial response to view	Reflects Changes in arousal associated with short-term events (discrete environmental stimuli)	[9, 13, 25, 29]
SCL	√	√	Stress level	Reflect stress (arousing) responses to continuous environmental stimuli	[27, 30]
HR	√	√	Initial response/ Stress level	Incresed HR indicates stress or arousal (excitement) and lower HR indicates resting or cognitive engagement	[13, 25, 29, 31]
HF-HRV	√	√		Increased level reflects relaxation	[32]
LF-HRV	√	√		the variability the lower frequencies represents a mixture of stress and relaxation	[8]
LF/HF	√	√		a higher ratio indicates elevated stress level and a low value indicates more relaxation	[33-35]

HRV_a	√	Indicates the variation in duration between two successive heart beats where decreased HRVa indicates stress while increased HRVa is related to lower performance anxiety	[27]
BVA	√	Reflects relative changes in the volume of blood in vessels where increased stress (arousing) activity decreasing BVA while decreased stress increasing BVA	[24, 36, 37]

A4.3 Analysis and Results

A4.3.1 Subjective Evaluation Reliability

To test the reliability of the view perception questionnaire (i.e., the questionnaire consistently reflects the construct that is measuring [38] (i.e., view quality)), the Cronbach's alpha (α) test [39] was used. The Cronbach's alpha ranges from 0 to 1 where α = 0 reflects no internal consistency (i.e., none of the items are correlated with one another), and α = 1 indicates perfect internal consistency (i.e., all items are perfectly correlated with one another). In the first experiment on view perception (appendix A2), the questionnaire had a Cronbach's α= 0.94, attaining the accepted range (0.70-0.80) [38]. Although the result indicated that the questionnaire is measuring the same construct (view quality), the detailed analysis indicated that the complexity parameter had a lower correlation with the overall questionnaire (r=0.35) as indicated in Table A4-4. I.e., if the "complexity" parameter was removed, the final Cronbach's α= 0.94 would have been enhanced.

Table A4-4. Reliability test of view quality questionnaire

Questionnaire Item	Item-Total Correlation *r*	Cronbach's α if item deleted	Total Cronbach's α

Fascinating	0.90	0.93	0.94
Being away	0.89	0.93	
Excitement	0.87	0.93	
Size	0.80	0.94	
Pleasantness	0.86	0.93	
Content	0.86	0.93	
Interest	0.88	0.93	
Complexity	0.35	0.97	

This might have occurred due to misinterpretation of the parameter meaning by participants. To account for this, in the following experiment, the complexity item was measured with an additional question and the reliability retesting revealed enhanced results (total questionnaire Cronbach's α= 0.97) and complexity correlated higher to the questionnaire construct (*r*=0.83). The results presented in Table A4-5 indicates a higher reliability of the second questionnaire.

Table A4-5. Reliability retest of view quality questionnaire

Questionnaire Item	Item-Total Correlation	Cronbach's α if item deleted	Total Cronbach's α
Fascinating	0.92	0.97	0.97
Being away	0.91	0.97	
Excitement	0.93	0.97	
Size	0.87	0.98	
Pleasantness	0.94	0.97	
Content	0.93	0.97	
Interest	0.91	0.97	
Complexity	0.83	0.97	

Hence, the questionnaire used in the second experiment on view perception in appendix A3 is more internally consistent and measures the same construct (view quality). The high value of Cronbach's α= 0.97 and high correlation between the items and the overall questionnaire indicate that when analysing data in future studies, the view quality can be assessed by using a total score that consists of the individual scores of each parameter [40].

A4.3.2 Correlation Analysis

A4.3.3 Subjective and Physiological Correlation for View Perception from Different Observing Locations

In this analysis, only 28 of the subjective responses were used corresponding to those used in the physiological analysis. Data correlations were detected using Spearman's correlation coefficient (r_s) which minimises the effect of extreme values and violations in normal distribution [38, 41]. Table A4-6, Table A4-7, and Table A4-8 present the correlations between the subjective recovery data and view perception questionnaire items, the physiological data and questionnaire items, and correlations between subjective recovery data and physiological recovery measures, respectively. The tables indicate the correlation coefficients and the significance of correlations (*p*-value).

To control type I error of rejecting the null hypothesis when it is true [14], the significant threshold of *p*-value was adjusted from 0.05 to 0.005 to identify the significant criterion, yet, the values less than 0.05 will be considered as suggestive [42]. The interpretation of the magnitude of the correlation was derived using ($r \geq 0.20$, 0.50, and 0.80), as an indication for 'small', 'moderate', and 'large' effect sizes, respectively [43].

Table A4-6 indicates significant negative correlations between the self-reported stress after recovery and the view perception items: fascinating, being away, excitement, pleasantness, content, and interest; with comparative magnitude. The self-reported stress was not significantly negatively related to the view's perceived size and complexity.

Reported PA was relatively significantly related to fascinating, being away, excitement, and interest items on view perception with small magnitude. PA was not significantly related to perceived size and pleasantness with comparative magnitude, and not related to view content and complexity (negligible magnitudes). Furthermore, reported NA was not significantly related to any of view perception items, all with negligible magnitude (r<0.20).

It can be inferred by the data in Table A4-6 that the increase in perceived view quality of the view are comparatively related to decreased reported stress during recovery from task performance, and increased reported PA.

Table A4-6. Correlations between subjective recovery measures and view perception questionnaire

Items		Fascinating	Being away	Excitement	Size	Pleasantness	Content	Interest	Complexity
Stress	r_s	-0.40	-0.32	-0.35	-0.26	-0.32	-0.37	-0.30	-0.02
	P	0.00**	0.00*	0.00*	0.02 n.s.	0.00*	0.00*	0.00*	0.83 n.s.
PA	r_s	0.32	0.35	0.34	0.26	0.28	0.15	0.34	0.03
	P	0.00*	0.00**	0.00*	0.01 n.s.	0.01 n.s.	0.18 n.s.	0.00 *	0.76 n.s.
NA	r_s	-0.07	0.02	-0.12	0.08	-0.05	-0.12	-0.05	-0.12
	P	0.51 n.s.	0.86 n.s.	0.27 n.s.	0.49 n.s.	0.66 n.s.	0.30 n.s.	0.65 n.s.	0.26 n.s.

* weakly significant; ** significant; *** highly significant; n.s. not significant
r<0.20= negligible; 0.20≤r<0.50= small; 0.50≤r<0.80= moderate; r≥0.80= large

Table A4-7 indicates no significant correlation between HR during recovery and view perception items with negligible magnitudes (r<0.20). LF-HRV showed a negative significant correlation with being away and content items with small magnitudes, and non-significant negative relation with the remaining items except for complexity which showed negligible correlation. HF-HRV was not significantly related to any of the view perception items; however, it showed small correlation magnitudes for being away, content, and interest. Non-significant negative correlations between LF/HF ratio and all view perception items were identified;

however, they were comparative for interest, content, fascinating, being away, and excitement, negligible for the remaining items. Furthermore, no significant correlations were found between SCL during recovery and view perception items with negligible magnitudes (r<0.20).

Table A4-7. Correlations between physiological recovery data and view perception items

Items		Fascinating	Being away	Excitement	Size	Pleasantness	Content	Interest	Complexity
HR	r_s	-0.04	0.04	0.04	0.11	-0.11	-0.15	0.01	-0.08
	P	0.71 n.s.	0.72 n.s.	0.70 n.s.	0.32 n.s.	0.30 n.s.	0.18 n.s.	0.95 n.s.	0.49 n.s.
LF-HRV	r_s	-0.26	-0.31	-0.24	-0.26	-0.23	-0.32	-0.28	0.02
	P	0.02 n.s.	0.00 *	0.03 n.s.	0.02 n.s.	0.04 n.s.	0.00*	0.02 n.s.	0.87 n.s.
HF-HRV	r_s	0.17	0.20	0.13	0.14	0.11	0.21	0.20	0.02
	P	0.13 n.s.	0.07 n.s.	0.24 n.s.	0.20 n.s.	0.31 n.s.	0.06 n.s.	0.09 n.s.	0.82 n.s.
LF/HF	r_s	-0.21	-0.27	-0.22	-0.14	-0.16	-0.21	-0.27	-0.03
	P	0.05 n.s	0.01 n.s	0.04 n.s	0.20 n.s.	0.15 n.s.	0.06 n.s.	0.01 n.s	0.78 n.s.
SCL	r_s	-0.09	-0.08	-0.02	-0.16	-0.06	-0.11	-0.06	-0.11
	P	0.43 n.s.	0.45 n.s.	0.88 n.s.	0.16 n.s.	0.57 n.s.	0.29 n.s.	0.57 n.s.	0.34 n.s.

* weakly significant; ** significant; *** highly significant; n.s. not significant
r<0.20= negligible; 0.20≤r<0.50= small; 0.50≤r<0.80= moderate; r≥0.80= large

Table A4-8 indicates that self-reported stress and NA were not related to any physiological measure. Informed PA by participants is positively related to the HR with small magnitude.

Table A4-8. Correlations between subjective recovery measures and physiological recovery measures

Items		HR	LF-HRV	HF-HRV	LF/HF	SCL
Stress	r_s	0.12	0.18	-0.14	0.27	-0.19
	P	0.24 n.s.	0.10 n.s.	0.21 n.s.	0.01 n.s.	0.10 n.s.
PA	r_s	0.30	0.08	0.02	-0.06	-0.12
	P	0.01 n.s.	0.47 n.s.	0.90 n.s.	0.61 n.s.	0.27 n.s.
NA	r_s	0.07	0.04	-0.07	0.13	-0.06
	P	0.56 n.s.	0.72 n.s.	0.54 n.s.	0.24 n.s.	0.59 n.s.

* weakly significant; ** significant; *** highly significant; n.s. not significant
r<0.20= negligible; 0.20≤r<0.50= small; 0.50≤r<0.80= moderate; r≥0.80= large

A4.3.4 Subjective and Objective Correlations for View Perception from Different Window Sizes

In this analysis, 25 of the subjective and physiological responses were used. Data correlations were detected using Spearman's correlation coefficient (r_s) which minimises the effect of extreme values and violations in normal distribution [38]. Table A4-9, Table A4-10, Table A4-11, Table A4-12 present the correlations between the subjective recovery data and view perception questionnaire items, the physiological data and questionnaire items, correlations between subjective recovery data and physiological recovery measures, and Correlations between physiological initial response data and view perception items respectively. The interpretations of *p*-value and the magnitudes of the correlation are similar to those used in the previous section.

Table A4-9 indicates non-significant negative correlations between the self-reported stress after recovery and all view perception items all with negligible magnitude ($r<0.20$). Reported PA was positively significantly related to all view perception items fascinating, being away, excitement, and interest with considerable magnitude ($r>0.30$). Nevertheless, reported NA was not significantly related to any of view perception items, all with negligible magnitude ($r<0.20$).

Once more, it can be inferred by the data in Table A4-9 that the increase in perceived fascinating, being away, excitement, size, pleasantness, content, and interest of the view is related to an increase in reported PA.

Table A4-9. Correlations between subjective recovery measures and view perception questionnaire

Items		Fascinating	Being away	Excitement	Size	Pleasantness	Content	Interest	Complexity
Stress	r_s	-0.06	-0.13	-0.07	-0.10	-0.07	-0.05	-0.02	-0.01
	P	0.25 n.s.	0.07 n.s.	0.23 n.s.	0.14 n.s.	0.23 n.s.	0.30 n.s.	0.41 n.s.	0.46 n.s.
PA	r_s	0.37	0.43	0.41	0.42	0.33	0.38	0.40	0.36
	P	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**
NA	r_s	0.02	-0.04	0.12	0.03	0.03	0.01	0.08	0.13
	P	0.42 n.s.	0.35 n.s.	0.10 n.s.	0.38 n.s.	0.37 n.s.	0.44 n.s.	0.19 n.s.	0.07 n.s.

* weakly significant; ** significant; *** highly significant; n.s. not significant
r<0.20= negligible; 0.20≤r<0.50= small; 0.50≤r<0.80= moderate; r≥0.80= large

Table A4-10 indicates a significant negative relation between HR and being-away item, non-significant negative correlations with small magnitude with fascinating, size, pleasantness, interest, complexity, and positive negligible relation with excitement and content (r<0.20). LF-HRV showed a negative significant correlation with view content and non-significant negative relation with the remaining items with small magnitudes (r≈0.2), except for complexity which showed negligible correlation. HF-HRV was significantly related to fascinating, pleasantness, content, and interest items and non-significantly related to the remaining items all with small magnitudes. Comparative negative significant correlations between LF/HF ratio and all view perception items were identified except for complexity which had a non-significant correlation with negligible magnitude. Both BVA and HRV_a did not show any significant correlation with questionnaire items. Furthermore, negative non-significant correlations between SCL during recovery and view perception items were found with small and negligible magnitudes (r<0.20).

Table A4-10. Correlations between physiological recovery data and view perception items

Items		Fascinating	Being away	Excitement	Size	Pleasantness	Content	Interest	Complexity
HR	r_s	-0.20	-0.24	0.15	-0.20	-0.20	0.15	-0.20	-0.20
	P	0.02 n.s.	0.00*	0.05 n.s.	0.02 n.s.	0.01 n.s.	0.05 n.s.	0.01 n.s.	0.01 n.s.

LF-HRV	r_s	-0.20	-0.19	-0.19	-0.17	-0.21	-0.23	-0.19	-0.12
	P	0.01 n.s.	0.02 n.s.	0.02 n.s.	0.02 n.s.	0.01 n.s.	0.00*	0.02 n.s.	0.10 n.s.
HF-HRV	r_s	0.23	0.20	0.20	0.21	0.22	0.28	0.23	0.20
	P	0.00*	0.03 n.s.	0.01 n.s.	0.01 n.s.	0.00*	0.00*	0.00*	0.02 n.s.
LF/HF	r_s	-0.26	-0.25	-0.29	-0.31	-0.28	-0.32	-0.25	-0.14
	P	0.00**	0.00**	0.00**	0.00**	0.00**	.00**	0.00**	0.06 n.s.
HRV_a	r_s	0.02	0.04	0.01	0.04	-0.05	0.02	-0.02	-0.04
	P	0.40 n.s.	0.34 n.s.	0.47 n.s.	0.33 n.s.	0.28 n.s.	0.42 n.s.	0.42 n.s.	0.34 n.s.
BVA	r_s	-0.10	-0.03	-0.02	-0.08	-0.04	-0.02	-0.07	-0.09
	P	0.13 n.s.	0.39 n.s.	0.43 n.s.	0.20 n.s.	0.35 n.s.	0.40 n.s.	0.22 n.s.	0.15 n.s.
SCL	r_s	-0.17	-0.17	-0.14	-0.13	-0.11	-0.11	-0.09	-0.10
	P	0.03 n.s.	0.02 n.s.	0.06 n.s.	0.07 n.s.	0.10 n.s.	0.12 n.s.	0.16 n.s.	0.12 n.s.

* weakly significant; ** significant; *** highly significant; n.s. not significant
r<0.20= negligible; 0.20≤r<0.50= small; 0.50≤r<0.80= moderate; r≥0.80= large

Table A4-11 indicates no significant correlation between self-reported stress, PA, and NA and physiological recovery measures with negligible magnitudes.

Table A4-11. Correlations between subjective recovery measures and physiological recovery measures

Items		HR	LF-HRV	HF-HRV	LF/HF	BVA	HRV_a	SCL
Stress	r_s	-0.02	0.02	0.01	0.04	-0.05	-0.05	-0.01
	P	0.41 n.s.	0.43 n.s.	0.47 n.s.	0.33 n.s.	0.29 n.s.	0.29 n.s.	0.48 n.s.
PA	r_s	0.13	-0.01	-0.07	-0.11	0.14	0.14	0.18
	P	.07 n.s.	0.47 n.s.	0.23 n.s.	0.12 n.s.	0.05 n.s.	0.05 n.s.	0.02 n.s.
NA	r_s	-0.09	0.14	0.06	0.08	-0.01	-0.02	0.01
	P	0.30 n.s.	0.11 n.s.	0.52 n.s.	0.41 n.s.	0.40 n.s.	0.40 n.s.	0.44 n.s.

* weakly significant; ** significant; *** highly significant; n.s. not significant
r<0.20= negligible; 0.20≤r<0.50= small; 0.50≤r<0.80= moderate; r≥0.80= large

For the initial response of the physiological data, significant negative correlations were found between HRV_a and fascinating and pleasantness items with comparative magnitude, and non-significant negative correlations were found with the remaining items with small and negligible magnitudes. No other significant correlations were found as detailed in Table A4-12.

Table A4-12. Correlations between physiological initial response data and view perception items

Items		Fascinating	Being away	Excitement	Size	Pleasantness	Content	Interest	Complexity
HR	r_s	-0.13	-0.01	-0.07	-0.06	-0.10	-0.13	-0.10	-0.06
	P	0.08 n.s.	0.47 n.s.	0.23 n.s.	0.25 n.s.	0.14 n.s.	0.08 n.s.	0.14 n.s.	0.27 n.s.
LF-HRV	r_s	0.07	0.14	0.07	0.16	0.12	0.05	0.10	-0.05
	P	0.22 n.s.	0.06 n.s.	0.21 n.s.	0.04 n.s.	0.10 n.s.	0.30 n.s.	0.14 n.s.	0.31 n.s.
HF-HRV	r_s	-0.06	-0.09	-0.05	-0.13	-0.11	-0.05	-0.09	-0.01
	P	0.24 n.s.	0.16 n.s.	0.28 n.s.	0.08 n.s.	0.11 n.s.	0.28 n.s.	0.16 n.s.	0.47 n.s.
LF/HF	r_s	0.06	0.09	0.06	0.10	0.10	0.07	0.07	-0.02
	P	0.27 n.s.	0.16 n.s.	0.24 n.s.	0.13 n.s.	0.13 n.s.	0.21 n.s.	0.23 n.s.	0.42 n.s.
HRV_a	r_s	-0.24	-0.13	-0.19	-0.16	-0.24	-0.23	-0.17	-0.20
	P	0.00**	0.08 n.s.	0.02 n.s.	0.04 n.s.	0.00**	0.01 n.s.	0.03 n.s.	0.01 n.s.
BVA	r_s	-0.13	-0.07	-0.09	-0.06	-0.06	-0.06	-0.20	-0.18
	P	0.07 n.s.	0.21 n.s.	0.16 n.s.	0.25 n.s.	0.24 n.s.	0.25 n.s.	0.02 n.s.	0.02 n.s.
SCR	r_s	-0.07	-0.09	-0.05	-0.03	-0.12	-0.08	-0.11	0.01
	P	0.21 n.s.	0.17 n.s.	0.28 n.s.	0.37 n.s.	0.09 n.s.	0.18 n.s.	0.12 n.s.	0.48 n.s.

* weakly significant; ** significant; *** highly significant; n.s. not significant
r<0.20= negligible; 0.20≤r<0.50= small; 0.50≤r<0.80= moderate; r≥0.80= large

A4.4 Discussion

This research has explored the reliability of the constructed subjective questionnaire on view perception in addition to the correlation between physiological measures and subjective responses on view perception. Reliability and correlation analyses were conducted for two sets of data collected based on view perception observed from different locations in the virtual office environment, and view perception from different window sizes to validate the use of the proposed methodology to quantify view quality perception.

The results of view perception reliability analysis indicated high internal consistency for the data collected in both experiments with improved results for the questionnaire used in the second experiment on view perception, by adding a question on perceived complexity of the view. For future research on view perception, a similar questionnaire can be used, and data collected for individual parameters can be used as a total score of view quality [40], which will facilitate the subjective data analysis. Nevertheless, an additional study to conduct test-retest reliability is needed (i.e., to provide an indication of stability over time for responses obtained with repeated testing using the same participants) [44, 45].

The correlation analysis between the view perception items and both the physiological and subjective recovery data further confirmed the adequacy of the quantifying method of view perception used in the two experiments conducted on view perception. I.e., a subjectively preferred high-quality view is a view that provides restorativeness. The correlations found in this analysis were between small and moderate thresholds. Nevertheless, those degrees of correlations are acceptable values compared to the findings of studies investigating the relations between subjective and physiological data (i.e., significant correlation values between 0.2 and 0.5 are usually reported) [46-48].

In the correlation analysis on view perceived from different locations, the subjective stress during recovery was negatively related to view quality ($0.3 \leq r \leq 0.4$). PA reported by participants was significantly positively related to the view quality parameters ($r \geq 0.3$) except for complexity and content, and no correlations were found for the NA. The second correlation analysis on view perceived from different window sizes showed similar results for PA data. This indicates that when participants observed the views after a stressful task, views with higher quality were more able to promote positive feelings including activeness, attentiveness, inspiring, alertness, and determination as measured by the PA scale [49]. Moreover, PA was consistently directly related to enhanced view quality, hence, could be used as a measure of view quality. Therefore, these findings provide evidence that a high-quality view is associated with enhanced subjective recovery from stress (i.e., enhanced psychological state of the participants during recovery from stress) [24].

Correlations between view quality and some of the physiological signals during recovery were also identified. In the first correlation analysis, LF-HRV and LF/HF during recovery found to be negatively related to a wide range of perceived view quality parameters ($0.2 \leq r \leq 0.3$). In the second correlation analysis, HR, LF-HRV, and LF/HF showed negative correlations with a wide variety of view perception parameters ($0.2 \leq r \leq 0.3$), while SCL was negatively correlated with fascinating and being away parameters ($r \approx 0.2$). I.e., an increase in view quality is related to a decrease in physiological stress (Table A4-3). This was further confirmed by positive relations between all view quality parameters and HR-HRV ($0.2 \leq r \leq 0.3$) which reflects relaxation. Hence, the results validate the proposed methodology to objectively quantify view perception and indicate that if the affective response of visual stimuli (views) is positive, the following physiological events will be also positive [24].

The results indicate that some of the physiological parameters were more adequate to elicit initial responses to view (i.e., when participants observed the view for the first time) including HRV_a and LF-HRV while others showed to be effective to measure recovery from stress (including HR, LF-HRV, HR-HRV, LF/HF, and SCL) when the stress-recovery methodology is applied.

The correlation analysis between evaluated view parameters and initial physiological responses (i.e., when participants first observed the view) revealed a positive correlation with LF-HRV for the size parameter and significant negative correlation between HRV_a and fascinating, pleasantness, content, interest, complexity, and excitement parameters. Higher LF-HRV reflects arousal (i.e., excitement) while lower HRV_a reflects increased mental work [48], which might indicate more cognitive engagement with the observed view. As the HRVa found to be correlated to a wider range of view parameters, it might be more adequate to be used to objectively quantify view quality by the initial response (i.e., observing views without stress -recovery).

During recovery from stress, SCL, LF-HRV, and LF/HF found to be decreasing with enhanced view quality while HF-HRV found to be increasing, hence, these measures are recommended to quantify the view quality by its restorativeness. Nevertheless, in both correlational analyses, LF-HRV and LF/HF results were more consistent and might be more adequate during pilot testing in the early stages of view perception studies.

An additional analysis was conducted on subjective and physiological recovery measures to explore whether the latter is sufficient to describe stress-recovery in similar research. In the first analysis, self-reported stress was positively related to LF/HF ($r \approx 0.3$) which is relevant to previous results in the literature indicating that increased LF/HF levels reflect higher stress [33-35]; however, no correlation was found for subjective recovery from stress and any of the physiological and subjective measures in the second analysis. This indicates that the association between psychological and physiological stress are not consistent, and both should be used to quantify restorativeness.

While the correlations provided are promising, the correlational values ranged between small and moderate and similar studies are needed before considering only one form of evaluation of view perception (i.e., subjective or objective). Nevertheless, the correlation analysis provided a guide on the best signals to use for each part of the research (during initial observing or as a stress-recovery measure) and shows how the physiological data collected can be interpreted concerning view perception quality.

A4.5 Conclusion

In this study, further analysis was conducted on the subjective and objective (physiological) data to provide more validity and to streamline the proposed methodology to quantify view perception for future research. This was conducted via a reliability test for the subjective preference questionnaire on view perception and correlational analysis between the subjective and objective responses collected to evaluate view perception during two individual experiments. The main findings of this study are:

- The proposed questionnaire to subjectively quantify view perception showed high reliability (internal consistency) and the various selected questions on view parameters measure the same construct (i.e., view quality), hence, can be used to subjectively quantify view quality.
- Both correlation analyses showed accepted correlations between view perception items and physiological recovery measurements, indicating that the subjectively preferred view is a view with restorative quality (i.e., a view that provides recovery from stress); which validates the proposed methodology to quantify the view quality based on its restorativeness.
- More physiological measures collected during recovery from stress were correlated to view perception parameters compared to those collected

during the initial response. Hence, both procedures are encouraged to be used to quantify view quality.

- HRV_a is recommended to quantify view quality by the initial response (i.e., observing different views), while SCL, LF-HRV, LF/HF and HF-HRV are recommended to quantify the view quality by its restorativeness.
- Physiological data indicated different trends (positive and negative correlations) during the different experiment events (i.e., initial response and during recovery), which should be carefully addressed in similar studies.

The detected correlations in this study were between small and moderate thresholds, although similar values are accepted in literature, it might indicate the need for further studies in order to confirm these correlations and replace the questionnaires with exclusively objective physiological data or vice versa. Meanwhile, both subjective assessment of the view and physiological data are needed for view quality assessment.

Nevertheless, utilizing similar methodology described in this course of work to quantify view perception, besides visual and thermal comfort and energy performance parameters, will further enhance the buildings' envelope performance and provide an inclusive approach to evaluate emerging windows' technologies performance.

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Declaration of Interest

None.

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Appendix B

Statements About Joint Authorship for The Published Papers

Statement About Joint Authorship for Paper 1

The description of the extent of this contribution to the joint paper (Developing an Innovative Method for Visual Perception Evaluation in a Physical-Based Virtual Environment)

Fedaa Abd-Alhamid has done the most significant intellectual contribution to this work, in terms of finding the study aim, designing the study's method, arranging equipment purchasing, acquiring the data, statistically analysing the collected data from the experiment, drawing conclusions, writing the manuscript in paper format to be published, and follow up reviewers' comments up until publishing. The co-authors have provided valuable contribution as follows:

- Yupeng Wu (Jack), is the main supervisor who supervised all stages of this research paper, from designing to publishing. Jack provided valuable comments and suggestions to enhance the manuscript to be of a high-quality and helped in providing the equipment needed to conduct the experiment.

- John Calautit, the second supervisor who supervised the work in this paper, provided technical help with the equipment and provided valuable comments and suggestions to enhance the manuscript.

- Michael Kent, the advisor of Fedaa, who has rigorously examined the work in this paper and guided throughout the different phases of the experiment. In addition, Michael helped in the paper manuscript by provided valuable comments and suggestions and proofread the paper.

- Chris Bennett, who helped during the pilot test and provided technical support by assisting in photometric measurements in the experiment room and assisting in executing the planned method of generating the Virtual environment.

I agree with the description of the extent of this contribution to the joint papers described above.

The description of the extent of this contribution to the joint paper (Developing an Innovative Method for Visual Perception Evaluation in a Physical-Based Virtual Environment)

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I agree with the description of the extent of this contribution to the joint papers described above.

YUPENG WU [illegible]

Name:…………………

Date:……02/04/20……………

The description of the extent of this contribution to the joint paper (Developing an Innovative Method for Visual Perception Evaluation in a Physical-Based Virtual Environment)

Fedaa Abd-Alhamid has done the most significant intellectual contribution to this work, in terms of finding the study aim, designing the study's method, arranging equipment purchasing, acquiring the data, statistically analysing the collected data from the experiment, drawing conclusions, writing the manuscript in paper format to be published, and follow up reviewers' comments up until publishing. The co-authors have provided valuable contribution as follows:

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I agree with the description of the extent of this contribution to the joint papers described above.

Name: ....

Date:11/06/2020

The description of the extent of this contribution to the joint paper (Developing an Innovative Method for Visual Perception Evaluation in a Physical-Based Virtual Environment)

Fedaa Abd-Alhamid has done the most significant intellectual contribution to this work, in terms of finding the study aim, designing the study's method, arranging equipment purchasing, acquiring the data, statistically analysing the collected data from the experiment, drawing conclusions, writing the manuscript in paper format to be published, and follow up reviewers' comments up until publishing. The co-authors have provided valuable contribution as follows:

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I agree with the description of the extent of this contribution to the joint papers described above.

Name:JOHN CALAUTIT…………………

Date:01/09/20…………………..

The description of the extent of this contribution to the joint paper (Developing an Innovative Method for Visual Perception Evaluation in a Physical-Based Virtual Environment)

Fedaa Abd-Alhamid has done the most significant intellectual contribution to this work, in terms of finding the study aim, designing the study's method, arranging equipment purchasing, acquiring the data, statistically analysing the collected data from the experiment, drawing conclusions, writing the manuscript in paper format to be published, and follow up reviewers' comments up until publishing. The co-authors have provided valuable contribution as follows:

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- John Calautit, the second supervisor who supervised the work in this paper, provided technical help with the equipment and provided valuable comments and suggestions to enhance the manuscript.

- Michael Kent, the advisor of Fedaa, who has rigorously examined the work in this paper and guided throughout the different phases of the experiment. In addition, Michael helped in the paper manuscript by provided valuable comments and suggestions and proofread the paper.

- Chris Bennett, who helped during the pilot test and provided technical support by assisting in photometric measurements in the experiment room and assisting in executing the planned method of generating the Virtual environment.

I agree with the description of the extent of this contribution to the joint papers described above.

Name:..C.A.Bennett...

Date:..1/4/20.........

Statements About Joint Authorship for Paper 2

The description of the extent of this contribution to the joint paper (Evaluating the Impact of Viewing Location on View Perception Using a Virtual Environment)

Fedaa Abd-Alhamid has done the most significant intellectual contribution to this work, in terms of finding the study aim, designing the study’s method, arrange purchasing equipment, acquiring the data, statistically analysing the data collected from the experiment, drawing conclusions, writing the manuscript in a paper format to be published, and follow up reviewers’ comments up until publishing. The co-authors have provided valuable contribution as follows:

- Yupeng Wu (Jack), is the main supervisor who supervised all stages of this research paper, from designing to publishing. Jack provided valuable comments and suggestions to enhance the manuscript to be of a high-quality and helped in providing the equipment needed to conduct the experiment.

- John Calautit, the second supervisor who supervised the work in this paper, provided technical help with the equipment and provided valuable comments and suggestions to enhance the manuscript.

- Michael Kent, the advisor of Fedaa, who has rigorously examined the work in this paper and guided throughout the different phases of the experiment. In addition, Michael helped in the paper manuscript by provided valuable comments and suggestions and proofread the paper.

I agree with the description of the extent of this contribution to the joint paper described above.

The description of the extent of this contribution to the joint paper (Evaluating the Impact of Viewing Location on View Perception Using a Virtual Environment)

Fedaa Abd-Alhamid has done the most significant intellectual contribution to this work, in terms of finding the study aim, designing the study's method, arrange purchasing equipment, acquiring the data, statistically analysing the data collected from the experiment, drawing conclusions, writing the manuscript in a paper format to be published, and follow up reviewers' comments up until publishing. The co-authors have provided valuable contribution as follows:

- Yupeng Wu (Jack), is the main supervisor who supervised all stages of this research paper, from designing to publishing. Jack provided valuable comments and suggestions to enhance the manuscript to be of a high-quality and helped in providing the equipment needed to conduct the experiment.

- John Calautit, the second supervisor who supervised the work in this paper, provided technical help with the equipment and provided valuable comments and suggestions to enhance the manuscript.

- Michael Kent, the advisor of Fedaa, who has rigorously examined the work in this paper and guided throughout the different phases of the experiment. In addition, Michael helped in the paper manuscript by provided valuable comments and suggestions and proofread the paper.

I agree with the description of the extent of this contribution to the joint paper described above.

Name:.....YUPENG WU...........

Date:.....02/04/20......

The description of the extent of this contribution to the joint paper (Evaluating the Impact of Viewing Location on View Perception Using a Virtual Environment)

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Name: ……………

Date:11/06/2020

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Name: JOHN CALAUTIT John Calautit

Date: 01/09/20