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Exploration on Effects of Tinted Glazing on Outdoor Views and Visual Experience Inside Hotel

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Abstract: Modern lifestyles result in people spending 90% of their time indoors, where windows serve as a unique component providing an outdoor view and enabling visual experiences. Chromogenic windows, which adjust both thermal and visual conditions, represent a promising fenestration system for achieving energy savings. However, the tinting properties and their effects on human responses to filtered window views have not been thoroughly explored. This study conducted an experimental test using a customised questionnaire to investigate eight distinct window conditions in a hotel building. Forty-five participants took part in this evaluation by observing photographs. The conclusions drawn are as follows: (1) All tinted windows were found to be less acceptable than clear windows; however, the bronze window was relatively preferred. (2) In terms of visual capacity, the red window had the most negative effect, followed by the blue window. (3) Considering the window views, the tinted windows significantly disturbed the view outside. These results have the potential to guide the development of chromogenic windows in practical applications in the future, particularly from the perspective of colour selection.

Keywords: window view; tinted glazing; visual perception

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1. Introduction

The built environment is critical for occupant performance and well-being, with substantial evidence indicating that most individuals spend about 70–90% of their time indoors, and adults are primarily indoors during work hours [1–4]. Consequently, the study of indoor environments is increasingly important, as these spaces can significantly influence occupant satisfaction and productivity [5,6]. In office settings, lighting and window views are two pivotal environmental factors [7,8]. Lighting not only facilitates vision but also impacts physiological and psychological functions [9]. Research has shown that optimal lighting can enhance sleep, alertness, and concentration, thereby improving productivity [10–13]. Furthermore, lighting is linked to psychological well-being and can profoundly affect both physical and mental health [14–16]. Window views also play a crucial role in the satisfaction of office occupants. For instance, a survey of 2500 office workers in the UK revealed that 89% considered an outside view essential [6]. Additionally, a study involving 318 occupants across three UK buildings highlighted that the type and quality of the window view significantly influenced their perceptions [17].

In recent decades, the development and application of advanced window technologies, particularly chromogenic windows, have significantly advanced building energy conservation efforts. These innovative fenestration systems can alter their transmittance in response to different stimuli, thereby automatically adjusting indoor thermal and visual conditions to optimise energy usage. While their benefits for energy efficiency are well recognised, there is an emerging interest in understanding how these windows affect human perception within occupied spaces. Chromogenic windows, which change tint based on environmental conditions such as sunlight exposure, temperatures electricity, etc., have a profound impact on various aspects of human perception. These effects include alterations in pleasure, alertness, eye fatigue, and mood fluctuations.

Despite the considerable focus on the technical and physiological impacts of chromogenic windows, there is a notable gap in research concerning their effects on occupants' perception of outdoor views. Outdoor views from windows play a crucial role in occupant satisfaction and psychological well-being. Views featuring natural landscapes are known to reduce stress and enhance productivity, while urban or obstructed views might not offer the same benefits. This study aims to explore the window views and visual experience affected by these kinds of tinting windows through an experimental investigation.

1.1. Evaluation Methods of Window Views

To evaluate the human response to window views, two methods are commonly used: on-site and virtual assessment, which involves photographs, virtual reality (VR), questionnaires, and scales.

In terms of on-site assessments, most studies were conducted in the same building, while different window views were captured to be evaluated by subjects [18]. Both full-scale and small-scale experimental rooms have been used, and questionnaires are the predominant methods to collect human responses subjectively. Chen et al. conducted a field experiment in a full-size office in Beijing, China, to assess how different types of glass affect mood and self-reported satisfaction. In their study, they installed seven different glass systems for evaluation, collecting data through a scaled questionnaire [19]. Meanwhile, Dubois et al. adopted a slightly different approach for their field evaluation, opting to use a 1:4 scale model of an office instead of a full-size office. In this setup, subjects evaluated four types of coloured glass, guided by a research assistant who facilitated the assessments in situ [20]. Besides using questionnaires to gather subjective data, objective measurements of emotional states were also taken. For instance, Elsadek et al. conducted their experiments in two separate offices in Shanghai, China [21]. Subjects were randomly assigned to these locations where their brain wave data were collected using the Emotiv EPOC EEG headsets. Additionally, the Ergo LAB "Human-Machine-Environment" synchronisation platforms were used to measure heart rate variability (HRV) and skin conductivity (SC), providing a comprehensive view of the physiological impacts [22].

For virtual evaluation methods, images are commonly utilised as a reliable approach for assessing window views. This technique addresses challenges such as dynamic daylight conditions and logistical restrictions, such as limited site access for participants and the need to evaluate a large array of window views efficiently. Kent and Stefano [23] conducted a controlled study in Singapore, comparing different window views under consistent conditions, such as identical window sizes and similar weather. Due to the need for consistency in comparative analysis and the impracticality of using field evaluations, the study utilised images to represent the window views. The validity of using images rather than field assessments involving human perception has been well considered based on the previous study. A meta-analysis by Stamps [24] of more than 1300 papers related to environmental psychology pointed to a strong correspondence (r = 0.86) between preferences obtained in situ and preferences obtained through photographs. In addition, research by Palmer and Hoffman [25] concluded that the use of photographs to present landscapes is highly correlated with actual landscapes, except in some special cases. Participants' subjective satisfaction was then gathered using a questionnaire. Similarly, Lin et al. used photographs to represent window views in their research, asking subjects to evaluate 80 different images. Data were collected based on participants' subjective ratings, analysing their preferences through both quantitative and qualitative assessments of the window view content [26]. For research on dynamic window views, alternative methodologies have been employed. Svobodova et al. [27] explored subjects' preferences for window views by presenting them with videos (sans audio) to simulate the changing environment. Furthermore, Rodriguez et al. [28]

utilised virtual reality (VR) technology to examine the impact of dynamic environmental attributes on user experience. In their experiment, participants were equipped with VR headsets in a laboratory setting and were randomly assigned to experience scenes in either a static or dynamic format. Their responses were captured through verbal questionnaires.

1.2. Human Response to Tinted Glazing

Previous research has established that the correlated colour temperature (CCT) is significantly influenced by tinted windows. Numerous studies have explored the relationship between CCTs and human perception, primarily under controlled, artificial lighting conditions due to the challenges of managing daylight exposure during experiments. However, there are fewer investigations into the effects of coloured glazing on indoor lighting environments. Even fewer studies have examined the impact of viewing through windows with coloured glazing, where the transmittance properties of the glazing material play a crucial role.

Research by Angelo et al. indicates that the hue of colour-coated glazing products can alter the perception of daylight colours experienced by individuals [29]. Arsenault et al. have determined a marked preference among building occupants for glazing in shades of bronze or other warm colours over blue, suggesting this preference might enhance the perception of brightness [30]. Chen et al.'s [19] investigation into the influence of glazing characteristics—namely, colour and light transmittance—on the subjective experiences of office employees in Beijing revealed that glazing in neutral tones is associated with an improvement in mood compared to coloured glazing. Furthermore, their study suggests that while higher levels of circadian stimulation can neutralise the impact of glazing colour and transmittance on alertness and drowsiness, in isolation, these glazing characteristics do not significantly affect such states. Dubois et al. [20] conducted a study in Denmark evaluating six different types of glass, focusing on their transmission levels. The findings indicated that glasses with higher transmission rates improved visibility and were more favourably rated by participants. The participants particularly noted improvements in the naturalness and aesthetic appeal of views through higher transmission glass. However, because the glazing types utilised in their study were less tinted yet more transmissive, it remains unclear whether the outcomes should be credited to colour, transmittance, or a synergy of the two. Arsenault et al. found that occupants generally prefer glazing with higher transmittance [29]. Boyce et al. investigated the lowest acceptable levels of transmittance by having participants observe realistic views from a simulated office window, determining that acceptable transmittance levels ranged from 25% to 38% [31].

Based on the relevant studies, it is found that window view is an overlooked part of tinted windows, and it is relatively difficult to evaluate since a variety of conditions should be controlled in real practice. In this study, an experiment was tailored to explore the window view and visual experience for occupants in a hotel with different tinted windows applied. The colours of glazing were selected based on the current advanced windows, a virtual assessment method with images was applied, and a customised questionnaire was utilised to collect the evaluation from participants.

2. Materials and Methods

2.1. Test Room Setup

The study was conducted in a hotel located in Huangshan City, Anhui Province, at coordinates 118°1′ E 30°1′ N. The research aimed to assess the impact of window views filtered by tinted windows and coloured glazing on individuals' subjective perceptions. Conditions were controlled as (1) the same outside view with different heights and (2) the same window component with different colours. To achieve these conditions, two identical experimental rooms were selected within the building. Both rooms were similarly oriented, measured approximately 4.2 m × 6.8 m × 3 m, and were situated on different floors. Each room featured a laboratory equipped with a standard single-glazed window measuring approximately 1.08 m × 1.50 m, with a window-to-wall ratio of 0.3, adhering to the experimental model's specifications.

2.2. Tinted Window Setup

Since chromogenic windows come in various colours with differing stimuli and transmittance levels, we collected films to simulate their typical conditions—clear, brown, blue, and red—to control variables for more reliable and effective results. These colours represent typical thermochromic, electrochromic, and red luminescent solar concentrating windows [32–34]. We selected the films from commercial products and measured them using a Thermo SCIENTIFIC Evolution Pro visible spectrophotometer. As is shown in Figure 1, each line colour represents the spectral transmittance of the corresponding coloured glazing films assessed for visual experience in this study. The spectral transmittances of the blue and bronze film are measured to be close to each other with slight differences within the wavelength range over 1000 nm; this could be explained by the interference effect, which depends on the relationship between the wavelength of light and the film thickness [35]. Even if the films are of different colours, their transmittance curves could be similar if their thickness and interference effects at specific wavelengths are comparable, whilst the red one has a lower transmittance between 400 and 600 nm of wavelength.

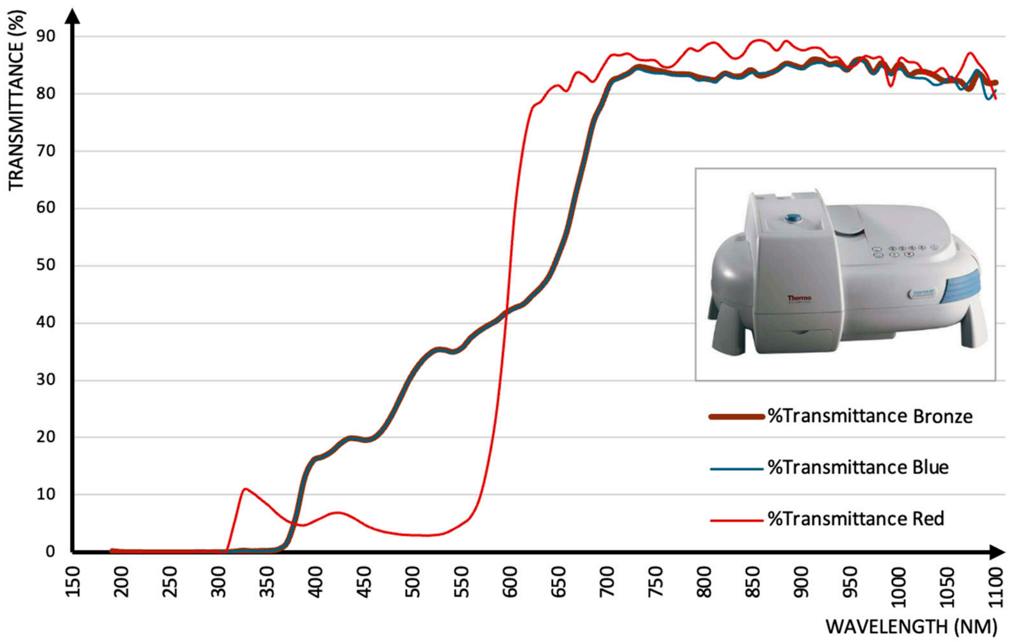

Figure 1. Spectral transmittance of three films and the visible spectrophotometer (inside).

Four window states were set up by applying tinted films to the inner surface of the windows in the experimental rooms. Four window conditions were assigned to each floor, including clear, bronze, blue, and red. As shown in Figure 2, the room on the lower floor (2nd floor) of the building has window conditions named as follows: C2 for the clear window without tint as a reference group (Figure 2a), BZ2 for the bronze window (Figure 2b), BL2 for the blue window (Figure 2c), and R2 for the red window (Figure 2d). Similarly, as depicted in Figure 2, the room on a relatively higher floor (4th floor) of the hotel building has corresponding window conditions named C4 for the clear window (Figure 3a), BZ4 for the bronze window (Figure 3b), BL4 for the blue window (Figure 3c), and R4 for the red window (Figure 3d). The views from the windows vary with height; from the lower floor, the mid-section of adjacent buildings can be seen, whereas from the higher floor, the tops of surrounding structures and a large area of sky are visible.

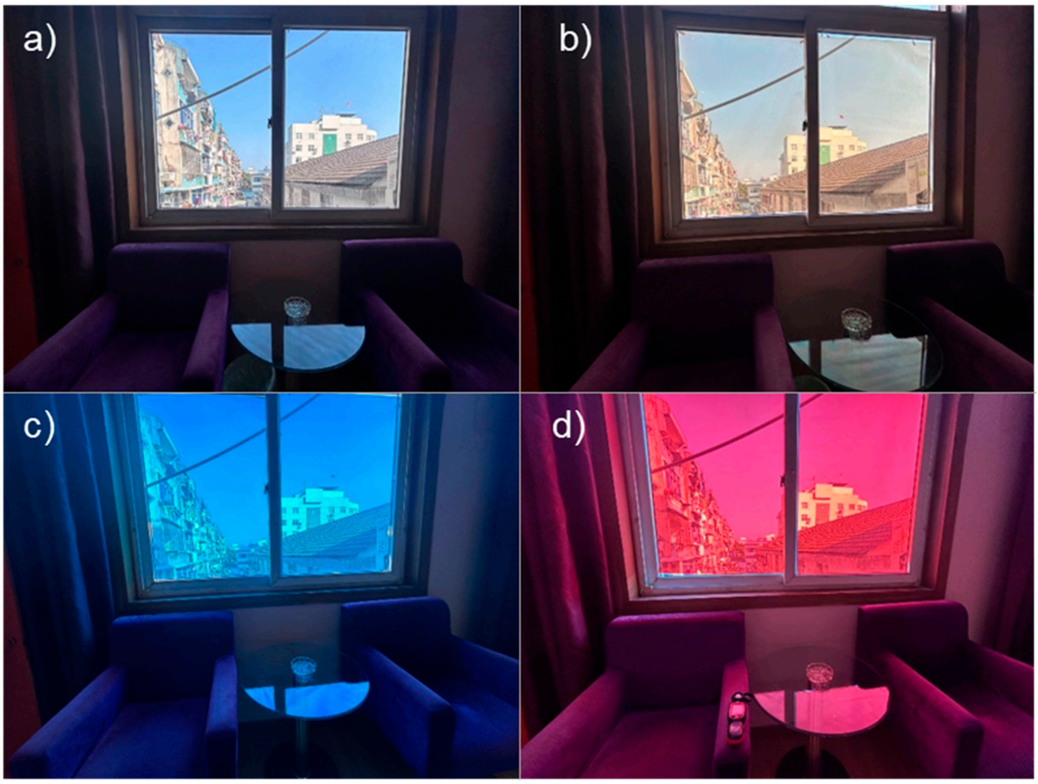

Figure 2. Four states of windows on lower floors: (**a**) clear (C2), (**b**) bronze (BZ2), (**c**) blue (BL2), and (**d**) red (R2).

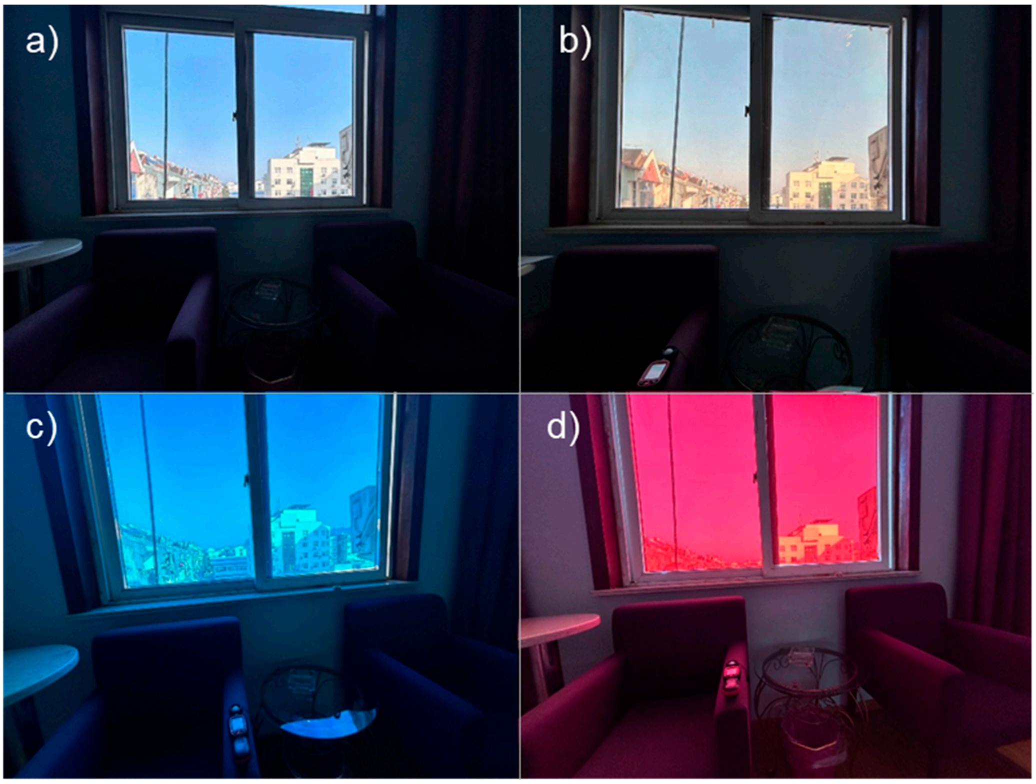

Figure 3. Four states of windows on higher floors: (**a**) clear (C4), (**b**) bronze (BZ4), (**c**) blue (BL4), and (**d**) red (R4).

Although on-site observation offers a more direct and realistic experience, it is subject to many uncontrollable variables such as changes in sunlight, temperature, and humidity. Additionally, on-site observation limits the number of participants. Palmer and Hoffman demonstrated that using photographs to represent landscapes correlates highly with actual views, although there are specific cases where photographs do not fully capture the natural setting [25]. To minimise distracting factors during the experimental phase, this study presented different window views to subjects using photographs instead of field observations. The photographs were taken from a position 1.0 m in front of the window using a camera equipped with a 13 mm wide-angle lens. All photographs were captured between 3 pm and 4 pm, deliberately avoiding direct sunlight and rainy conditions. Lighting conditions were consistently monitored using a portable illuminance meter (DELIXI) in the proposed hotel room located in Huangshan, Anhui, China, positioned on a tabletop within the subject's work area to ensure uniform illuminance across different window conditions.

2.3. Assumptions

Since this experiment relied on participants' subjective assessments, several assumptions were made to enable the feasibility of modelling and procedures:

- The basic mechanisms of visual processing are uniform across individuals.
- Participants' short-term memory is stable and reliable throughout the experiment.
- All participants have a baseline level of visual acuity and normal colour vision.
- The experimental environment is controlled for each participant to minimise external variables (e.g., thermal comfort, background noise, or distractions) that could affect visual perception.
- Participants can accurately imagine their perception of the given luminous environment based on the images provided.

2.4. Questionnaires Design

Thirteen questions were designed to obtain subjective assessments of different window conditions and the views through them. An online survey tool was utilised to distribute these questionnaires within the investigator's network. An ethics review was conducted in accordance with university guidelines and was successfully approved. As Table 1 shows, questions Q1, Q12, and Q13 focus on the general impression of the room's lighting conditions. Q2 assesses whether the brightness is sufficient. Questions Q3–Q6 address visual capability, while Q7–Q11 pertain to the views outside the window and visual comfort impacted by the tinted windows. A 5-level Likert scale was used for evaluations, where 1 represents the most negative response, 5 is the most positive, and 3 is neutral.

Table 1. Questionnaires used to collect human response to different window conditions.

Questions		***Bi-Polar Rating***					
Q1: With this lighting, the whole room looks?	Very uncomfortable	1	2	3	4	5	Very comfortable
Q2: What is the level of light on the desktop?	Very insufficient	1	2	3	4	5	Very sufficient
Q3: The textures and contours of the interior items are?	Very faint	1	2	3	4	5	Very accurate
Q4: The colours of the objects in the room look?	Very unnatural	1	2	3	4	5	Very natural
Q5: The reading problems in this lighting situation are?	Very laboured	1	2	3	4	5	Very easy
Q6: The contrast between the black and white writing on the paper is?	Very unclear	1	2	3	4	5	Very clear
Q7: The level of glare you perceive is?	Unbearable	1	2	3	4	5	Not at all
Q8: The view through the window is?	Very blurred	1	2	3	4	5	Very clear
Q9: What is the colour of the view from the window?	Very unnatural	1	2	3	4	5	Very natural
Q10: Your mood towards the view from the window was?	Very full	1	2	3	4	5	Very pleasant
Q11: The view from the window was?	Very unattractive	1	2	3	4	5	Very attractive
Q12: In general, the atmosphere created by the lighting is?	Very dull	1	2	3	4	5	Very pleasant
Q13: Is it acceptable to live in this window-conditioned light environment?	Very unacceptable	1	2	3	4	5	Very acceptable

2.5. Procedures

This study was conducted during the COVID-19 pandemic towards the end of 2022, which necessitated the use of an online survey with graphics instead of on-site testing. Following the survey invitation, a total of 45 valid responses were collected. The participants ranged in age from 18 to 50 years, with an average age of 30. The gender distribution included 23 females and 22 males, with none reporting colour vision defects. The questionnaire was divided into two sections, comprising a total of 107 questions. The first three items collected demographic information (gender and age) and an informational sheet, while items 4 through 107 asked participants to rate their preferences for eight window photographs. These questions explored participants' perceptions of visual comfort, brightness, naturalness, accuracy, uniformity, pleasantness, and overall comfort. To minimise the impact of the presentation order of the photographs on participants' perceptions, three different sequences were used: (a) clear–bronze–blue–red, (b) red–clear–bronze–blue, and (c) blue–clear–red–bronze.

2.6. Statistical Analysis

Since the Likert scale responses are a type of ordinal data, non-parametric statistical methods were used for the within-subjects comparisons by using the statistical analysis program SPSS 29. Initially, Friedman's ANOVA test was conducted to detect any significant differences among the eight window conditions. Subsequently, post hoc analyses using the Wilcoxon signed-rank test were performed to identify specific differences between each pair of conditions. Since the same hypotheses were tested multiple times using the Wilcoxon signed-rank test, Bonferroni–Holm corrections were applied to adjust the significance threshold to 0.00625.

3. Results

Comparisons were undertaken between different floors with windows installed initially, and then the results were categorised into three sections: general impression of the indoor environment, visual capacity, and window views under various window conditions.

3.1. Difference Detection between Window Conditions

Friedman's ANOVA test was used to detect differences among the eight window conditions. Table 2 indicates that all 13 questions yielded statistically significant results, demonstrating significant differences between certain window conditions.

Table 2. Friedman's ANOVA test on responses to questions with significant results.

Questions	*N*	*Chi-Square*	*df*	*p-Value*
Q1	45	202.102	7	<0.001 ***
Q2	45	134.039	7	<0.001 ***
Q3	45	113.375	7	<0.001 ***
Q4	45	178.785	7	<0.001 ***
Q5	45	153.137	7	<0.001 ***
Q6	45	153.292	7	<0.001 ***
Q7	45	185.869	7	<0.001 ***
Q8	45	181.257	7	<0.001 ***
Q9	45	210.632	7	<0.001 ***
Q10	45	180.854	7	<0.001 ***
Q11	45	180.519	7	<0.001 ***
Q12	45	171.585	7	<0.001 ***
Q13	45	184.630	7	<0.001 ***

*** highly significant.

Figure 4 presents the boxplots for responses to questions Q13, Q2, Q3, and Q8, which address the acceptance of the environment affected by tinted windows, overall brightness, visual clarity, and views outside. The distribution patterns for the lower floors (C2, BZ2, BL2, and R2) closely mirror those of the upper floors (C4, BZ4, BL4, and R4). Pairwise comparisons of the same-coloured windows across different floor levels show no significant differences (p-value > 0.00625). To avoid redundancy, subsequent analyses will utilise data from the lower floors.

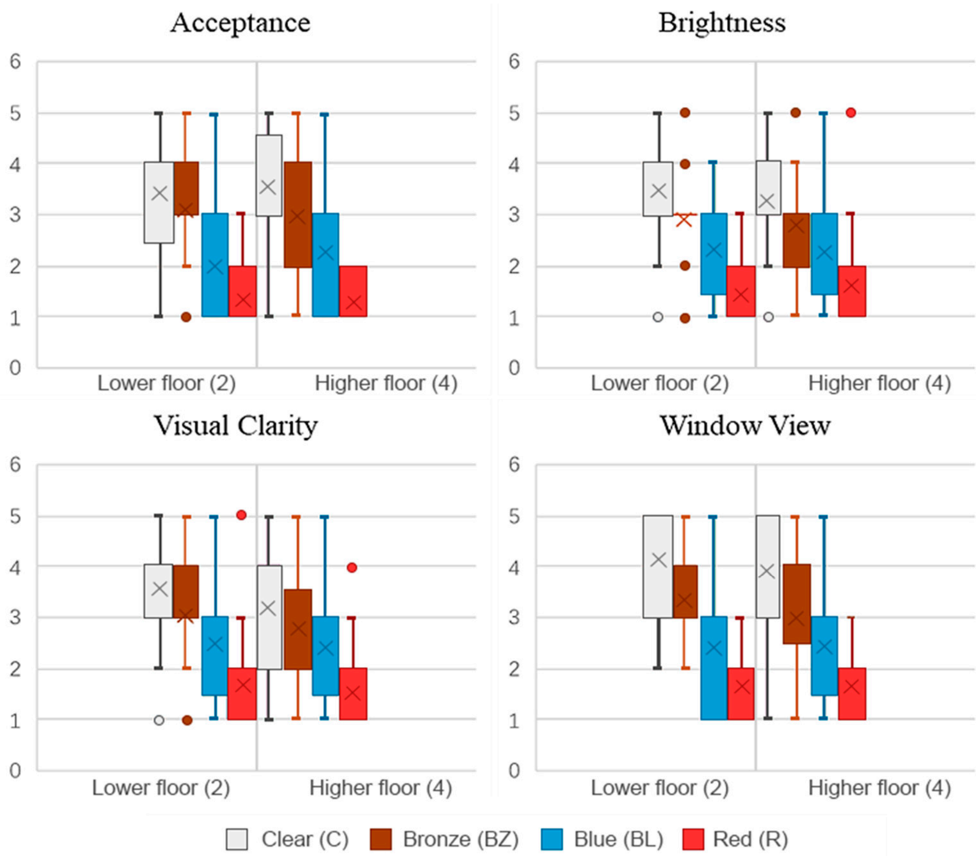

Figure 4. Boxplot of the answers to Q13 (acceptance), Q2 (brightness), Q3 (visual clarity), and Q8 (window view). Lower floor (2) from left to right is C2, BZ2, BL2 and R2, and higher floor (4) from left to right is C4, BZ4, BL4 and R4.

3.2. General Impression

Questions Q1, Q12, and Q13 were employed to gauge the overall perceptions of subjects in rooms equipped with tinted windows. Pairwise comparisons were conducted using the Wilcoxon signed-rank test, which yielded significant findings as presented in Table 3. In this context, 'M1' denotes the median value of the initial condition, and 'M2' represents the median value of the subsequent condition.

The data from Q1, which aimed to assess the comfort level of the occupants, indicate that rooms with clear windows were perceived as the most comfortable, followed by those with bronze windows. The comfort level diminished sequentially in the order of clear > bronze > blue > red window conditions. This non-parametric paired comparison relies on median values; for example, a median of four for C2 indicates that positive responses were frequently recorded, whereas a median of one for R2 signifies a high frequency of negative responses.

The findings from Q12, which explored the pleasantness of the atmosphere created by the tinted windows, reveal that most participants found the rooms with both bronze and clear windows enjoyable while the red windows were associated with unpleasant sensations. No significant differences were observed between the bronze and clear windows, leading to their classification as having an equivalent performance.

Table 3. Wilcoxon signed rank for answers to Q1, Q12, and Q13 with significant results.

M1-M2	M1	M2	Negative	Positive	Ties	Z	*p*-Value
Q1:The Whole Room Comfort Level							
BZ2–C2	3	4	26	6	13	−3.699	<0.001 ***
BL2–C2	2	4	39	1	5	−5.513	<0.001 ***
R2–C2	1	4	43	0	2	−5.77	<0.001 ***
BL2–BZ2	2	3	29	6	10	−4.37	<0.001 ***
R2–BZ2	1	3	42	0	3	−5.822	<0.001 ***
R2–BL2	1	2	24	1	20	−4.271	<0.001 ***
Q12:Pleasantness of Atmosphere							
BL2–C2	2	4	32	2	11	−4.923	<0.001 ***
R2–C2	1	4	38	0	7	−5.436	<0.001 ***
BL2–BZ2	2	3	28	4	13	−4.458	<0.001 ***
R2–BZ2	1	3	38	0	7	−5.464	<0.001 ***
R2–BL2	1	2	19	6	20	−3.311	<0.001 ***
Q13:Acceptance of Window Conditions							
BL2–C2	2	4	33	1	11	−5.06	<0.001 ***
R2–C2	1	4	39	0	6	−5.506	<0.001 ***
BL2–BZ2	2	3	30	5	10	−4.196	<0.001 ***
R2–BZ2	1	3	41	1	3	−5.626	<0.001 ***
R2–BL2	1	2	17	1	27	−3.563	<0.001 ***

Bonferroni–Holms corrected: *** highly significant.

Q13 focused on collecting responses regarding the acceptance of the window conditions. Consistent with the findings of Q12, it is noteworthy that significant differences were detected in all comparisons except between the conditions C2 and BZ2.

Table 4 addresses the assessment of perceived brightness, despite the photographs being taken under consistent illuminance conditions. The observed variations in brightness are due to the differences in colour temperature induced by the tinting of the windows. The data indicate that the window with no tint is perceived as significantly brighter than the others, with the red-tinted window exhibiting the lowest perceived brightness. The bronze-tinted window is noted to be marginally brighter than the blue-tinted window, a difference that is statistically significant with a *p*-value of 0.001.

Table 4. Wilcoxon signed rank for answers to Q2 with significant results.

M1-M2	M1	M2	Negative	Positive	Ties	Z	*p*-Value
Q2:Brightness							
BZ2–C2	3	4	24	6	15	−3.497	<0.001 ***
BL2–C2	2	4	33	2	10	−4.973	<0.001 ***
R2–C2	1	4	39	0	6	−5.514	<0.001 ***
BL2–BZ2	2	3	24	8	13	−3.250	0.001 **
R2–BZ2	1	3	36	1	8	−5.313	<0.001 ***
R2–BL2	1	2	25	2	18	−4.263	<0.001 ***

Bonferroni–Holms corrected: *** highly significant. ** significant.

3.3. Visual Capacity

Questions Q3, Q4, Q5, and Q6 collectively evaluate the visual experience within a room featuring tinted windows. A critical aspect of this study is determining whether visual acuity is preserved under optimal conditions using chromogenic windows. In this context, participants were presented with various objects, including furniture and printed papers, to assess visual clarity and colour accuracy; the findings are presented in Table 5.

Table 5. Wilcoxon signed rank for answers to Q3, Q4, Q5, and Q6 with significant results.

M1-M2	M1	M2	Negative	Positive	Ties	Z	*p*-Value
			Q3:Accurate				
BZ2–C2	3	4	22	7	16	−2.812	0.005 *
BL2–C2	2	4	29	2	14	−4.389	<0.001 ***
R2–C2	1	4	37	2	6	−5.325	<0.001 ***
R2–BZ2	1	3	36	1	8	−5.265	<0.001 ***
R2–BL2	1	2	25	5	15	−3.358	<0.001 ***
			Q4:Naturality of Colour Inside				
BL2–C2	2	4	39	2	4	−5.404	<0.001 ***
R2–C2	1	4	43	0	2	−5.761	<0.001 ***
BL2–BZ2	2	3	33	6	6	−4.426	<0.001 ***
R2–BZ2	1	3	41	1	3	−5.614	<0.001 ***
R2–BL2	1	2	22	3	20	−3.521	<0.001 ***
			Q5:Reading				
BL2–C2	2	4	33	4	8	−4.878	<0.001 ***
R2–C2	1	4	40	1	4	−5.591	<0.001 ***
BL2–BZ2	2	3	31	6	8	−3.696	<0.001 ***
R2–BZ2	1	3	42	1	2	−5.688	<0.001 ***
R2–BL2	1	2	24	1	20	−4.279	<0.001 ***
			Q6:Contrast				
BL2–C2	3	4	36	0	9	−5.344	<0.001 ***
R2–C2	2	4	42	0	3	−5.717	<0.001 ***
BL2–BZ2	3	3	29	4	12	−4.419	<0.001 ***
R2–BZ2	2	3	40	0	5	−5.601	<0.001 ***
R2–BL2	2	3	23	4	18	−3.801	<0.001 ***

Bonferroni–Holms corrected: *** highly significant; * weakly significant.

For Q3, which assesses the ability to discern textures and contours, responses indicated that clarity was highest with clear windows. Conversely, red-tinted windows significantly impaired visibility, leading to controversial outcomes. No statistically significant differences were observed between blue and bronze windows in terms of clarity; however, median values suggest a neutral response (a score of three) for bronze windows and a slightly negative response (a score of two) for blue windows, indicating reduced accuracy.

Regarding Q4, which focuses on the natural appearance of item colours, commonly referred to as colour-rendering issues, and Q5 and Q6, which explore reading difficulties and contrast in printed materials, respectively, the results were consistent. Clear windows performed comparably to bronze windows, with no significant differences noted. However, clear windows achieved the highest ratings overall, whereas red windows ranked lowest, with blue windows occupying an intermediate position.

These findings highlight the variability in visual perception and colour accuracy depending on the tint of the window, underscoring the importance of selecting appropriate chromogenic windows for environments where visual tasks are critical.

3.4. Window View Outside

Questions Q7–Q11 shown in Table 6 focus on subjective evaluations of the views through four types of tinted windows, addressing glare risks, clarity of view, naturalness of view, and mood-related issues. It is important to note that evaluating glare through static photographs has inherent limitations; nevertheless, the responses suggested that red and blue windows were associated with a noticeable level of glare, which participants found intolerable.

Table 6. Wilcoxon signed rank for answers to Q7, Q8, Q9, Q10, and Q11 with significant results.

M1-M2	M1	M2	Negative	Positive	Ties	Z	p-Value
				Q7:Glare			
BL2–C2	2	4	36	1	36	−5.269	<0.001 ***
R2–C2	1	4	42	0	42	−5.697	<0.001 ***
BL2–BZ2	2	4	32	5	32	−4.364	<0.001 ***
R2–BZ2	1	4	39	0	39	−5.486	<0.001 ***
R2–BL2	1	2	20	6	20	−3.455	<0.001 ***
				Q8:Clarity of Window View			
BZ2–C2	3	4	29	3	13	−4.189	<0.001 ***
BL2–C2	2	4	37	1	7	−5.378	<0.001 ***
R2–C2	2	4	43	0	2	−5.795	<0.001 ***
BL2–BZ2	2	3	29	8	8	−3.625	<0.001 ***
R2–BZ2	2	3	40	0	5	−5.593	<0.001 ***
R2–BL2	2	2	24	3	18	−3.989	<0.001 ***
				Q9:Naturality of Window View Outside			
BZ2–C2	3	4	25	2	18	−3.922	<0.001 ***
BL2–C2	2	4	38	3	6	−5.47	<0.001 ***
R2–C2	1	4	45	4	0	−5.915	<0.001 ***
BL2–BZ2	2	3	35	3	5	−4.915	<0.001 ***
R2–BZ2	1	3	44	4	1	−5.848	<0.001 ***
R2–BL2	1	2	21	2	22	−3.886	<0.001 ***
				Q10:Mood Caused by Window View			
BZ2–C2	3	4	23	5	17	−3.524	<0.001 ***
BL2–C2	2	4	34	2	9	−5.144	<0.001 ***
R2–C2	1	4	42	1	2	−5.734	<0.001 ***
BL2–BZ2	2	3	29	6	10	−4.331	<0.001 ***
R2–BZ2	1	3	40	0	5	−5.59	<0.001 ***
R2–BL2	1	2	21	4	20	−3.61	<0.001 ***
				Q11:Attractive			
BL2–C2	2	3	33	6	6	−4.545	<0.001 ***
R2–C2	1	3	43	1	1	−5.751	<0.001 ***
BL2–BZ2	2	3	28	8	9	−3.75	<0.001 ***
R2–BZ2	1	3	43	0	2	−5.81	<0.001 ***
R2–BL2	1	2	20	4	21	−3.614	<0.001 ***

Bonferroni–Holms corrected: *** highly significant.

For clarity and naturality of the views outside (Q8 and Q9), significant findings demonstrated a ranking from most to least positive as follows: clear > bronze > blue > red. This indicates that views through red windows may appear more artificial and blurred, potentially affecting the overall visual experience. Furthermore, the assessment of mood in relation to the pleasantness of the view showed a positive correlation with the clarity and naturalness ratings (Q8 and Q9).

Regarding Q11, which explored the attractiveness of the view outside, the results indicated generally low median values across all window types, with all scoring three or below. A comparative analysis between the bronze and clear windows revealed no significant differences in attractiveness levels. However, the red-tinted windows consistently received the lowest rankings, underscoring their negative impact on visual perception and mood.

These insights are crucial for understanding the psychological and perceptual effects of window tinting in architectural designs, especially in settings where the quality of view and visual comfort are paramount.

4. Discussion

As clear windows are commonly utilised in everyday environments, they were designated as the control group in this experiment. The statistical analysis revealed that the views from different floors did not significantly influence the participants' subjective impressions. However, the data indicated notable differences in subjective ratings across different window tints and colours, highlighting the influence of window colour on participants' perceptions. Concerning the aspect of floor levels, the experimental conditions showed that the views from various floors did not significantly affect the participants' subjective ratings. This may be attributed to the minimal variation in views between the floors within the scope of this study, suggesting that future research could further explore this aspect.

In terms of window colours, participants generally found the views through the 'clear' and 'bronze'-tinted windows more acceptable. In contrast, the 'red' and 'blue' tints were perceived as less favourable, with the 'red' tint receiving the lowest acceptance level. This is in stark contrast with the 'clear' condition, which was the most favoured, and aligns with research indicating that neutral-coloured glass tends to elicit more positive emotional responses than non-neutral glass. The significantly poorer performance of the red-tinted glass can be attributed to two main factors: the level of daylight and visual transmittance. Red glass, characterised by its intense colour and low visual transmittance, provides diminished daylight illumination [19], which likely contributed to the negative emotional responses observed in participants. This finding supports previous studies that emphasise the pivotal role of both the colour and transmittance of glass in affecting subjective assessments [20].

In addition, this experiment also considered the effect of coloured light on the results of the experiment. The research of Xie et al. [36] indicated that red light decreases feelings of calmness, relaxation, and pleasure and increases feelings of irritability and tension. Blue light decreases feelings of relaxation and stability and increases feelings of irritability. Therefore, when observing images of the window-scape, the window-scape and the coloured light work together to influence an impression of the individual. When comparing the 'blue' and 'red' tint conditions—both non-neutral—the participants were more receptive to the 'blue' windows. This preference could be due to the higher transmittance level of blue-tinted glass compared to red. This differentiation in reception and acceptance underlines the importance of considering both the aesthetic and functional properties of window glass in architectural designs to enhance occupant satisfaction and visual comfort.

Based on previous studies exploring chromogenic smart windows, warm-tinted windows are more acceptable in most situations [33]. This is significant since thermochromic windows, which primarily exhibit warm colours, are the most economical among chromogenic smart windows due to their low-cost materials and relatively simple manufacturing processes compared to electrochromic and photovoltaic windows [37]. Thermochromic windows respond to temperature variations automatically, requiring no additional cost for control or maintenance. Although they are still in the lab stage, various studies have demonstrated their potential for practical application [38–40]. This study further supports the feasibility of thermochromic windows by showing that bronze-tinted windows are particularly acceptable, adding to the evidence of their practical viability.

Limitations

The limitations of this study can be discussed in the following three aspects:

(1) Static Photographs and Dynamic Scenarios

In this study, subjective assessments were conducted using still photographs; however, such photographs fail to capture dynamic scenarios like moving clouds or crowd activity. Additionally, the photographs might not accurately represent daylight conditions compared to real-world observations.

To address these limitations, future research could employ video or VR technology to create more lifelike simulations, allowing subjects to experience and evaluate a more authentic environment. An on-site test will be conducted to validate the image testing results.

(2) Research Location and View Composition

This study was conducted in a public building, with photographs taken from its second and fourth floors. Consequently, the content composition of the two window views was similar, though not identical.

Future studies might consider including a broader range of views, such as those incorporating bodies of water or lush vegetation, to further explore their impact on subjects' emotional responses.

(3) Questionnaire Variability and Mood Influences

Moreover, the assessments in this experiment were conducted through questionnaires that participants could complete at different times and locations. This variability might have influenced their responses, as subjects' moods can vary significantly during different activities such as working, studying, eating, and resting. Therefore, while the subjective assessments were informative, it is important to acknowledge that they might not always align with objective responses.

Future research could incorporate physiological measures, such as heart rate variability (HRV) and skin conductivity (SC), to provide a more comprehensive evaluation of visual and emotional responses.

5. Conclusions

This study investigates the relationship between window glass colour, the content of window views, and the subjective impressions of individuals. Eight distinct window conditions were established for this experiment. Participants were requested to evaluate these conditions subjectively using a questionnaire. A statistical analysis was conducted on the collected data, revealing the following findings:

– For the overall impression of window conditions, tinted windows were generally found to be less acceptable than clear windows. Comfort levels decreased in the following order: clear (a score of four), bronze (a score of three), blue (a score of two), and red (a score of one). However, the bronze windows were relatively preferred, as there were no significant differences ($p > 0.00625$) in pleasantness and acceptance levels compared to the clear windows.
– In terms of visual capacity, the red windows (a score of one) had the most negative effect, followed by the blue windows (a score of two).
– Regarding window views, tinted windows significantly disrupted the view outside. The ranking from most to least positive was clear (a score of four), bronze (a score of three), blue (a score of two), and red (a score of one). The existing views outside the test room also influenced the results, with a score of three or below, indicating they were less attractive.

The results have the potential to provide guidance for developing chromogenic windows in practical applications in the future, particularly from the perspective of colour selection.

There are limitations to detecting dynamic scenarios by using static image testing, on-site validation, and research variability. Further studies will implement on-site experimental validation tests, utilising wearable devices such as eye-tracking glasses and physiological sensors, to gather more objective and precise data on human responses to indoor lighting environments. These studies might encompass a diverse array of landscapes, including urban, rural, and natural settings, to thoroughly evaluate the impact of different views on individuals' preferences and psychological well-being, providing more results to develop the feasibility of applying advanced glazing.

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Abbreviations

VR	Virtual reality
HRV	Heart rate variability
SC	Skin conductivity
CCT	Correlated colour temperature
C2/C4	Clear window on second/fourth floor
BR2/BR4	Bronze window on second/fourth floor
BL2/BL4	Blue window on second/fourth floor
R2/R4	Red window on second/fourth floor
M1	Median for the initial condition
M2	Median for the subsequent condition

References

1. Vischer, J.C. Towards an Environmental Psychology of Workspace: How People are Affected by Environments for Work. *Arch. Sci. Rev.* **2008**, *51*, 97–108. [CrossRef]
2. Barrett, P.; Barrett, L. The potential of positive places: Senses, brain and spaces. *Intell. Build. Int.* **2010**, *2*, 218–228.
3. Gupta, A.; David Cheong, K.W. Physical characterization of particulate matter and ambient meteorological parameters at different indoor–outdoor locations in Singapore. *Build. Environ.* **2007**, *42*, 237–245. [CrossRef]
4. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE). *2009 ASHRAE Handbook—Fundamentals* (I-P Edition); American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE): Atlanta, GA, USA, 2009.
5. Al Horr, Y.; Arif, M.; Kaushik, A.; Mazroei, A.; Katafygiotou, M.; Elsarrag, E. Occupant productivity and office indoor environment quality: A review of the literature. *Build. Environ.* **2016**, *105*, 369–389. [CrossRef]
6. Leder, S.; Newsham, G.R.; Veitch, J.A.; Mancini, S.; Charles, K.E. Effects of office environment on employee satisfaction: A new analysis. *Build. Res. Inf.* **2016**, *44*, 34–50. [CrossRef]
7. Veitch, J.A.; Newsham, G.R. Lighting Quality and Energy-Efficiency Effects on Task Performance, Mood, Health, Satisfaction, and Comfort. *J. Illum. Eng. Soc.* **1998**, *27*, 107–129. [CrossRef]
8. Ne'eman, E.; Sweitzer, G.; Vine, E. Office Worker Response to Lighting and Daylighting Issues in Workspace Environments: A Pilot Study. *Energy Build.* **1984**, *6*, 159–171. [CrossRef]
9. Zhang, R.; Campanella, C.; Aristizabal, S.; Jamrozik, A.; Zhao, J.; Porter, P.; Ly, S.; Bauer, B.A. Impacts of dynamic LED lighting on the well-being and experience of office occupants. *Int. J. Environ. Res. Public Health* **2020**, *17*, 7217. [CrossRef]
10. Blume, C.; Garbazza, C.; Spitschan, M. Effects of light on human circadian rhythms, sleep and mood. *Somnologie* **2019**, *23*, 147–156. [CrossRef]
11. Viola, A.U.; James, L.M.; Schlangen, L.J.; Dijk, D.J. Blue-enriched White Light in the Workplace Improves Self-reported Alertness, Performance and Sleep Quality. *Scand. J. Work. Environ. Health* **2008**, *34*, 297–306. [CrossRef]
12. Lim, J.; Dinges, D.F. Sleep Deprivation and Vigilant Attention. *Ann. N. Y. Acad. Sci.* **2008**, *1129*, 305–322. [CrossRef] [PubMed]
13. Ratcliff, R.; Van Dongen, H.P.A. Sleep deprivation affects multiple distinct cognitive processes. *Psychon. Bull. Rev.* **2009**, *16*, 742–751. [CrossRef] [PubMed]
14. De Kort, Y.A.W.; Smolders, K.C.H.J. Effects of dynamic lighting on office workers: First results of a field study with monthly alternating settings. *Light. Res. Technol.* **2010**, *42*, 345–360. [CrossRef]
15. Georgieva, E.; Karamalakova, Y.; Miteva, R.; Abrashev, H.; Nikolova, G. Oxidative stress and cocaine intoxication as start points in the pathology of cocaine-induced cardiotoxicity. *Toxins* **2021**, *9*, 317.
16. Lindahl, J.; Thulesius, H.; Rask, M.; Wijk, H.; Edvardsson, D.; Elmqvist, C. Assessing the Supportiveness of Healthcare Environments' Light and Color: Development and Validation of the Light and Color Questionnaire (LCQ). *HERD* **2021**, *14*, 130–144. [CrossRef] [PubMed]

17. Ne'Eman, E.; Hopkinson, R. Critical minimum acceptable window size: A study of window design and provision of a view. *Light. Res. Technol.* **1970**, *2*, 17–27. [CrossRef]
18. Vasquez, N.G.; Rupp, R.F.; Andersen, R.K.; Toftum, J. Occupants' responses to window views, daylighting and lighting in buildings: A critical review. *Build. Environ.* **2022**, *219*, 109172. [CrossRef]
19. Chen, X.; Zhang, X.; Du, J. Glazing type (colour and transmittance), daylighting, and human performances at a workspace: A full-scale experiment in Beijing. *Build. Environ.* **2019**, *153*, 168–185. [CrossRef]
20. Dubois, M.-C.; Cantin, F.; Johnsen, K. The effect of coated glazing on visual perception: A pilot study using scale models. *Light. Res. Technol.* **2007**, *39*, 283–304. [CrossRef]
21. Elsadek, M.; Liu, B.; Xie, J. Window view and relaxation: Viewing green space from a high-rise estate improves urban dwellers' wellbeing. *Urban For. Urban Green.* **2020**, *55*, 126846. [CrossRef]
22. Gilchrist, K.; Brown, C.; Montarzino, A. Workplace settings and wellbeing: Greenspace use and views contribute to employee wellbeing at peri-urban business sites. *Landsc. Urban Plan.* **2015**, *138*, 32–40. [CrossRef]
23. Kent, M.; Schiavon, S. Evaluation of the effect of landscape distance seen in window views on visual satisfaction. *Build. Environ.* **2020**, *183*, 107160. [CrossRef]
24. Stamps, A.E. Use of Photographs to Simulate Environments: A Meta-Analysis. *Percept. Mot. Ski.* **1990**, *71*, 907–913. [CrossRef]
25. Palmer, J.F.; Hoffman, R.E. Rating reliability and representation validity in scenic landscape assessments. *Landsc. Urban Plan.* **2001**, *54*, 149–161. [CrossRef]
26. Lin, T.-Y.; Le, A.-V.; Chan, Y.-C. Evaluation of window view preference using quantitative and qualitative factors of window view content. *Build. Environ.* **2022**, *213*, 108886. [CrossRef]
27. Svobodova, K.; Vojar, J.; Sklenicka, P.; Filova, L. Presentation Matters: Causes of Differences in Preferences for Agricultural Landscapes Displayed via Photographs and Videos. *Space Cult.* **2018**, *21*, 259–273. [CrossRef]
28. Rodriguez, F.; Garcia-Hansen, V.; Allan, A.; Isoardi, G. Subjective responses toward daylight changes in window views: Assessing dynamic environmental attributes in an immersive experiment. *Build. Environ.* **2021**, *195*, 107720. [CrossRef]
29. Matusiak, B.; Anter, K.F.; Angelo, K. *Color Shifts behind Modern Glazing*; University College of Arts, Crafts and Design: Stockholm, Sweden, 2012. Available online: https://www.academia.edu/12686254/Colour_shift_behind_modern_glazing (accessed on 11 June 2024).
30. Arsenault, H.; Hébert, M.; Dubois, M.-C. Effects of glazing colour type on perception of daylight quality, arousal, and switch-on patterns of electric light in office rooms. *Build. Environ.* **2012**, *56*, 223–231. [CrossRef]
31. Boyce, P.; Eklund, N.; Mangum, S.; Saalfield, C.; Tang, L. Minimum acceptable transmittance of glazing. *Int. J. Light. Res. Technol.* **1995**, *27*, 145–152. [CrossRef]
32. Vossen, F.M.; Aarts, M.P.; Debije, M.G. Visual performance of red luminescent solar concentrating windows in an office environment. *Energy Build.* **2016**, *113*, 123–132. [CrossRef]
33. Liang, R.; Kent, M.; Wilson, R.; Wu, Y. The effect of thermochromic windows on visual performance and sustained attention. *Energy Build.* **2021**, *236*, 110778. [CrossRef]
34. Liang, R.; Kent, M.; Wilson, R.; Wu, Y. Development of experimental methods for quantifying the human response to chromatic glazing. *Build. Environ.* **2019**, *147*, 199–210. [CrossRef]
35. Gunde, M.K.; Orel, Z.C. Thickness-Dependent Optical Effects in Infrared Reflection-Absorption Spectra of a Fairly Thick Polymer Layer. *Appl. Spectrosc.* **2002**, *56*, 24–30. [CrossRef]
36. Xie, X.; Cai, J.; Fang, H.; Tang, X.; Yamanaka, T. Effects of colored lights on an individual's affective impressions in the observation process. *Front. Psychol.* **2022**, *13*, 938636. [CrossRef] [PubMed]
37. Rashidzadeh, Z.; Matin, N.H. A Comparative Study on Smart Windows Focusing on Climate-Based Energy Performance and Users' Comfort Attributes. *Sustainability* **2023**, *15*, 2294. [CrossRef]
38. Feng, Y.-Q.; Lv, M.-L.; Yang, M.; Ma, W.-X.; Zhang, G.; Yu, Y.-Z.; Wu, Y.-Q.; Li, H.-B.; Liu, D.-Z.; Yang, Y.-S. Application of New Energy Thermochromic Composite Thermosensitive Materials of Smart Windows in Recent Years. *Molecules* **2022**, *27*, 1638. [CrossRef] [PubMed]
39. Deng, B.; Zhu, Y.; Wang, X.; Zhu, J.; Liu, M.; Liu, M.; He, Y.; Zhu, C.; Zhang, C.; Meng, H. An Ultrafast, Energy-Efficient Electrochromic and Thermochromic Device for Smart Windows. *Adv. Mater.* **2023**, *35*, e2302685. [CrossRef]
40. Jin, Q.; Long, X.; Liang, R. Numerical analysis on the thermal performance of PCM-integrated thermochromic glazing systems. *Energy Build.* **2022**, *257*, 111734. [CrossRef]