

Exploration on Research Methods for Exploring Human Response to Luminous Environment with Chromogenic Windows Applied

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Abstract: Chromogenic windows enable both energy-saving and daylighting regulation. However, the human response to the luminous environment affected by them is difficult to test, since their features of dynamic change and tinting automatically. This study explores the research methods, including experimental design and statistical analysis, by literature review and an experiment demonstration. The results show that a proper size of the test room is significant to obtain desired data, and the advanced VR technologies have the potential to be applied for testing these dynamic variables. Bayesian approaches are recommended to be tried and get more accurate interference about the experimental results.

Keywords: Chromogenic windows; Building luminous environment; Human response; Statistical analysis; Experimental design

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1. Introduction

Over the last decades, sustainable building technologies have been well investigated. A large amount of energy use in buildings makes it sense that energy-saving approaches are desired. The chromogenic smart window (e.g., electrochromic, thermochromic, gasochromic, and photochromic) is a type of innovative approaches to regulating indoor thermal and luminous conditions ^[1]. That can reduce the undesired solar heat gain dynamically transmitted into the building, diminishing the possibility of overheating by solar radiation and achieving energy conservation simultaneously. Various studies have been undertaken to explore their energy performance, and electrochromic windows have commercial products, other types of chromogenic windows are still on the lab stage. Since the chromogenic windows have features of tinting with their solar transmittance changing during the work, such as blue, brown, etc., the indoor luminous environment is affected by the chromatic glazing as well. Human response to the daylighting conditions affected by the chromogenic windows is significant to be figured out before these innovative smart windows being applied in practice.

However, the features of ‘dynamic’ and ‘tinting’ improve the difficulties of experimental methods on human response to chromogenic windows, and statistical analysis influences the results as well. This study aims to explore the appropriate research methods specified for this type of dynamic chromatic glazing applied in working space, by using a self-designed experiment and literature review. It is proposed to give more particular suggestions to improve and accelerate the development of these energy-efficient smart windows.

2. Literature review of research methods

This section demonstrated the research methods from three aspects, including experimental design for windows' application, statistical analysis tools, and innovative virtual reality (VR) technologies.

2.1. Experimental design

According to the size, the experiments for human response can be classified into two types:

- (1) Small-scale, where participants can look into the test chamber and observe the given targets and complete questionnaires [2-3].
- (2) Full-scale, where participants are invited to walk into the test room and undertake some visual or non-visual tasks [4].

Both methods are valid to obtain desired results, however, the subjective assessment about the whole indoor luminous environment by using a small-scale test room cannot restore the perception overall. the test of colour shifts affected by different window glazing (**Figure 1. (a)**) [5], the observers are hard to receive all information indoors from the top view. While if a full-scale experiment was applied to test different types of windows, the change of window conditions will not be convenient as the small-scale one, as is shown in **Figure 2. (b)** [4].

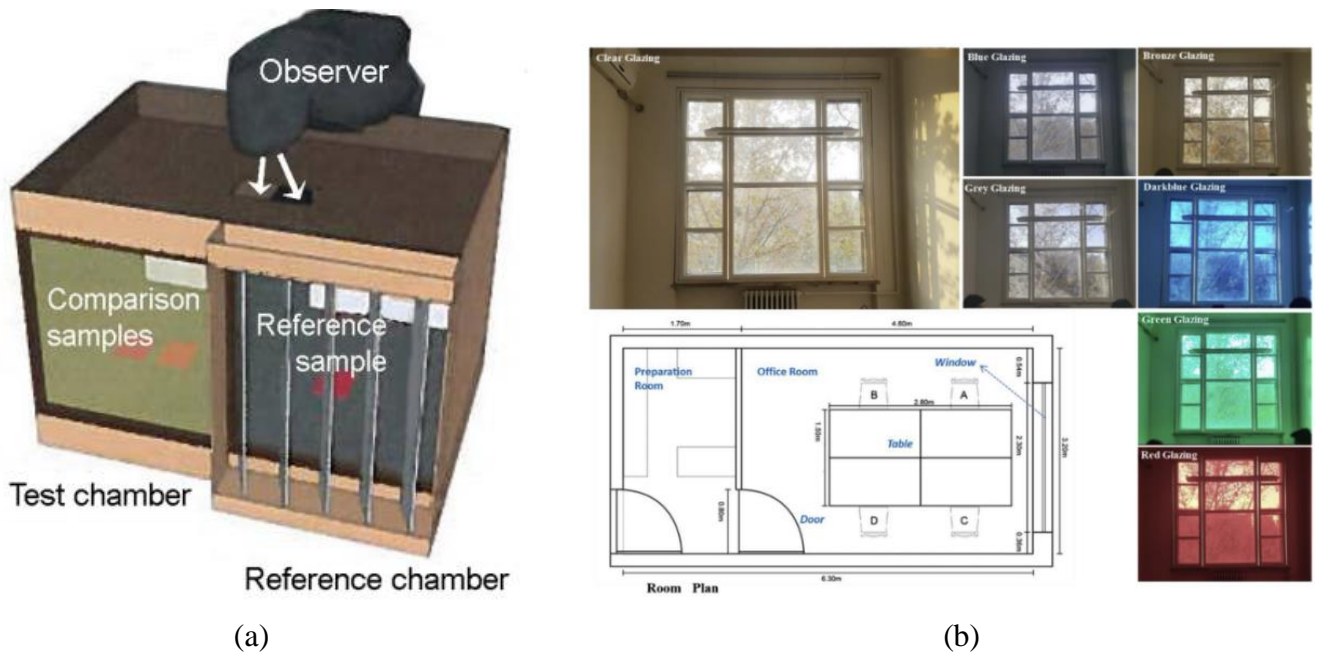


Figure 1. Two sizes of test room (a) small scale; (b) full scale [4, 5]

2.2. Statistical analysis

Most of the evaluations on the luminous environment are based on the subjective response and objective performance from samples of occupants drawn from the building users. Therefore, statistical analysis has to be applied to deal with these results, in the perspective of analysis methods, most of the studies chose to use the classical frequentist approach, such as null hypothesis significance testing (NHST) depending on the sample size and magnitude of effect, to detect the results performance [6-8].

Bayesian inference is proposed to be an alternative method to implement the analysis [9]. Different from frequentist approaches, Bayesian estimation can incorporate prior knowledge (i.e., based on existing knowledge), and combine the likelihood from the new data, resulting in a posterior distribution. In other words, Bayesian analysis is used to re-allocate the degree of belief across possibilities [9]. Additionally, the Bayesian hypothesis test can quantify evidence that the data provide for the null hypothesis (H0) and the alternative hypothesis (H1). Lee et al [10] developed a Bayesian approach for providing accurate predictions

for personalized thermal preference profiles. Another study conducted by Wang and Hong ^[11] used the Bayesian inference approach to define new occupants comfort temperature range in office buildings of the USA. Xiong et al ^[12] also use the Bayesian approach to infer the visual satisfaction profile in daylight office based on previously collected data from experiments. Therefore, it is believed that the Bayesian approach can be applied to validate experimental models and achieve more accurate inference based on known information.

2.3. VR technologies

Since the chromogenic windows have the features of dynamic changing of solar transmittance, which increase the difficulty of setting up and control the experiments. In the past decades, the combined use of advanced VR technology and building design have realized the test of user behaviour and achieve energy-saving ^[13-14]. Shahinmoghadam et al. integrated the Internet of Things (IoT) and VR in the development of immersive VR applications for real-time monitoring of thermal comfort conditions. The prototype of the system has been implemented and used to support the consistency between the system output and the actual thermal sensation observed under various conditions ^[15]. Vittori et al. redesigned an office through VR and recorded the sense of presence, with a satisfaction rate of 76%. The VR design environment is used to reproduce key variables of design, involving artificial lighting colour temperatures. VR evaluation significantly reduces the cost and achieves human-centred energy efficiency ^[16]. Yeom et al. used VR to determine the best window-to-wall ratio of buildings that can achieve energy efficiency and a healthy working environment ^[17]. It can be seen that VR is helpful for the building environment evaluation with multiple variables.

3. An experiment of thermochromic windows

The thermochromic (TC) window is one of the most promising smart windows that tints with temperature difference automatically, a series of experiments were designed to test the human response to the luminous environment with thermochromic window applied, exploring the specific experimental and analysis methods.

3.1. Experiment setting up

To achieve both Immersive experience of participants and convenient change of window conditions, a test cubicle with the dimension of 1.5m (length)*1.2m (width)*2.1m (height) was built, and the indoor luminous affected by TC window were simulated by a virtual window so that the illuminance levels could be controlled manually. Three window conditions with two horizontal illuminance levels (100lux and 350lux): 1) TC_Bronze, standing for VO₂ nanoparticle film; 2) clear glazing as a reference; 3) TC_Blue, representing the iron-liquid based TC material, which can tint from clear to blue during the working. Detailed parameters of experimental conditions were shown in **Table 1**.

During the experiment I and II, 31 participants were invited to attend the test, respectively, they were required to complete objective tasks (Landolt rings visual test) and subjective assessment (questionnaires) under each window condition, the sequence of window conditions was randomized.

3.2. Data analysis using Bayesian approaches

The collected data were analysed by firstly using the classical frequentist approach for the experiment I and II separately, and the results show that TC_Bronze is relatively more acceptable in general. Since different participants were used for these two experiments, the both classical Mann-Whitney U test and Bayesian approaches were tried to do the independent paired comparisons between I and II, to do exploration on analysis methods. For Bayesian approaches, BF₁₀ present the evidence for supporting H₀ (i.e., no

difference) and H1 (i.e., difference significant).

Table 1. illuminance and colour temperatures (CCT) under three window conditions.

Window conditions	Experiment I		Experiment II	
	Illuminance(lux)	CCT(K)	Illuminance(lux)	CCT(K)
1. TC_Bronze		4053		4056
2. Clear	100lux ($\pm 5\%$)	4903	350lux ($\pm 5\%$)	4911
3. TC_Blue		6934		7054

Table 2. Mann-Whitney U test and Bayesian Mann-Whitney U test of questions with significant difference between Experiment I and II.

	Window conditions	Mdn1-Mdn2		Mann-Whitney U test			Bayesian one	
		100lux	350lux	Statistic	p	Effect Size (r_B) ^a	BF ₁₀ ^b	W
Brightness	TC_Bronze	2	3	271.5	0.002*	-0.435	4.625*	689.5
	Clear	3	4	266.0	0.002*	-0.446	8.175*	695.0
	TC_Blue	2	3	328.5	0.024*	-0.316	1.682*	632.5
Uniformity	TC_Bronze	3	4	315.0	0.017*	-0.344	2.869*	646.0
	TC_Blue	2	4	335.0	0.035*	-0.303	1.268*	626.0
Alertness	TC_Bronze	3	3	310.5	0.007*	-0.354	1.658*	650.5
	TC_Blue	3	3	330.0	0.027*	-0.313	1.106*	631.0
Pleasantness	TC_Bronze	2	3	232.5	< .001*	-0.516	8.982*	728.5
	TC_Blue	2	3	328.0	0.023*	-0.317	1.005*	633.0
Naturalness	TC_Bronze	2	3	338.0	0.038*	-0.297	1.285*	623.0
Comfort	TC_Bronze	2	4	237.5	< .001*	-0.506	13.269*	723.5
	Clear	2	3	288.5	0.004*	-0.400	4.767*	672.5
Acceptance	TC_Bronze	2	4	244.0	< .001*	-0.492	10.282*	717.0
	Clear	2	3	262.5	0.001*	-0.454	7.468*	698.5
	TC_Blue	2	3	336.5	0.037*	-0.300	1.549*	624.5

* significant

a Effect size (r_B): $r_B < 0.3$ small effect, $0.3 < r_B < 0.5$ moderate effect, $r_B > 0.5$ large effect.;

b Bayes Factor (BF₁₀) : $0.33 < BF_{10} < 1$ is anecdotal evidence for H₀; BF₁₀ = 1 is no evidence; $1 < BF_{10} < 3$ is anecdotal evidence for H₁; $3 < BF_{10} < 10$ is moderate evidence for H₁; $10 < BF_{10} < 30$ is strong evidence for H₁; $30 < BF_{10} < 100$ is very strong evidence for H₁; BF₁₀ > 100 is decisive evidence for H₁.

It can be seen from the data in **Table 2.** that, brightness, uniformity, alertness, pleasantness, naturalness, comfort, and acceptance, the classical and Bayesian results are shown almost the same. However, classical results required both p and effect size (r_B) to show the degree of the difference caused by illuminance levels, while BF_{10} shows the difference straightforward with the finer classifications. A 5-level Likert scale was applied to all answers to the questions, and 1 is for the most negative answer, and 5 for the most positive one. In terms of medians, especially for Brightness and Acceptance, participants gave more positive answers during experiment II than that of experiment I under all of the three window conditions. Moreover, the results show that the uniformity, alertness, pleasantness and comfort are all increased in experiment II with higher illuminance levels under the TC window conditions. That means that under the chromatic luminous environment, higher illuminance can lead to a more positive response. In **Table 2.**, the cases with the effect size falling into the moderate range and BF_{10} falling into the anecdotal range indicate that the Bayesian method is more detailed to show the degree of illuminance effect.

4. Conclusions

This study explored the experimental methods and innovative analysis approaches by literature review and an experiment about the human response to the TC windows application, the experiment used a test cubicle, which is smaller than a full-scale room but it is accessible for participants. The proper size of the test cubicle enables the quick change of the window conditions as well. A review of VR technologies applied to optimize the building environment indicated that VR technologies have the potential to simulate daylighting conditions filtered by different window types, and creating various illuminance, CCT and other lighting conditions. Additionally, Bayesian approaches are suggested to be applied for getting more accurate inference, especially for these phased and batched experiments.

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