Window views psychological effects on indoor thermal perception: a comparison experiment based on virtual reality environments

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Abstract. Previous studies have indicated that window views significantly impact residents' indoor thermal perception, but the exact pathways and extent of this cross-modal influence are not fully understood. This research explores how outdoor visual attributes affect indoor thermal comfort through visual-thermal interaction, potentially aiding energy reduction in built environments. Utilizing the Landscape Visual Quality Assessment (LVQA) method, the study quantified window views with five green visibility indicators in 16 virtual environments. The experiment involved 24 participants in two temperature settings, revealing that specific window view attributes notably affect thermal perception and emotional responses. Elevated Biophilic Design Attributes and a heightened Visible Green Index correlate with increased thermal comfort. An augmented Sky View Factor and Color Richness may be associated with an elevated thermal sensation. However, Observer Landscape Distance appears to have no significant correlation with thermal perception. The findings highlight that positive emotional dimensions correlate with improved thermal comfort and acceptance, whereas negative emotions are associated with discomfort. This study elucidates the interactive effects of window view attributes on thermal perception, providing valuable insights for energy-efficient outdoor environment design.

1 Introduction

Ensuring indoor thermal comfort in buildings while minimizing energy consumption is crucial for low-carbon living. Residential buildings, significantly contributing to urban energy use, are influenced by inhabitants' behaviors [1]. Achieving thermal comfort necessitates influencing residents' environmental control actions, a key aspect of energy-saving design [2], especially in high-density urban environments [3].

Windows, as a vital visual and design element of residential interiors, not only enhances thermal perceptions under the same physical conditions [4], reducing blood oxygen saturation and stress levels [5] but also affects residents' thermal comfort evaluations [6] and willingness to control their environment [7]. They allow greater tolerance for thermal comfort range deviations [8] and enable energy savings through adjusted settings [1]. Research has found that outdoor green landscapes can improve residents' cognitive recovery and thermal comfort [9][10]. Effective window view design can introduce this effect into indoor space and can also mitigate additional energy consumption caused by uncomfortable outdoor environments, as adverse external conditions increase the demand for indoor comfort, leading to more proactive climate control and higher energy use in buildings [11].

Recent studies on indoor thermal comfort have discovered that visual-thermal interaction—the effect of visual perception on thermal sensation [12] —can achieve comfort at lower energy costs [13]. Since thermal perception is a cognitive activity, therefore, like other cognitive activities, it is affected by emotions and stress levels [14][15], in a good pleasant visual environment, participants were in positive sentiment and thus tolerated greater deviations from the comfort range of the thermal environment [16]. Landscape, as a kind of visual stimulation, has been found to affect human physiological thermoregulation by influencing psychological conditions, and different environmental temperatures will also affect participants' architectural aesthetic preferences [17][18]. This phenomenon suggests that optimizing visual scenes can reduce the need for indoor climate control [19], aiding in overall energy reduction. However, current research on window views often focuses more on the correlation between green landscapes and psychological elements, with less emphasis on their specific impact on residents' indoor thermal perception. Thus, this study aims to fill this gap, exploring how window view elements affect indoor thermal perception through the following two hypotheses, providing insights for sustainable, energy-efficient design of residential windows and outdoor environments:

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(1) The green visibility element of the window view can significantly affect participants' thermal perception.

(2) Emotional evaluation toward window view elements can significantly affect residential indoor thermal perception.

2 Methodology

To quantify the physiological and psychological effects of different window view elements on thermal perception, this study initially defined and quantified five green visibility indicators. Subsequent research was conducted in a Virtual Reality (VR) environment to independently control environmental temperature and visual stimuli. Unlike real physical environments, VR environments enable the creation of simulated visual settings without affecting the separate control of thermal conditions, offering both authenticity and predictive accuracy [20]. The use of VR in this context also serves as an alternative to PMV prediction, contributing to the fine-tuned design of energy-efficient buildings [21][22][23].

2.1 Scenarios design

This study draws upon the Landscape Visual Quality Assessment (LVQA) methodology, integrating and constructing five key elements of green visibility to measure: Sky Visible Factor, SVF; Visible Green Index, VGI; Color Richness, CR; Biophilic Design Attributes, BHA; and Observer Landscape Distance, OLD, serving as physical assessment metrics.

Fig. 1. Scenarios Design.

SVF is the ratio of the solid angle of the visible sky to the entire hemisphere above the observer [24]. In this study, the sky visibility factor refers to the proportion of the sky in the visible part of the window view. Under the same conditions without tree shade, the thermal sensation voting (TSV) of high SVF scenes is closer to thermal neutrality in each season [25], which is also related to higher street comfort [26][27]. However, it is still unknown how the SVF corresponding to the window view will affect the thermal perception of indoor residents.

VGI is the most intuitive indicator for measuring the greenness of a window view. The proportion of visible greenery from a window is positively correlated with preference [28]. Windows with higher VGI values are associated with lower average radiant temperatures and higher thermal comfort.

Color is a critical dimension in determining residents' perception of a window view. Natural views with high color richness are more significantly associated with perceived restorative capacity and increased positive affect [29]. The measurement of color richness is conducted using the method developed by Hasler [30] for assessing Image CR, with the final Color Richness M value serving as an evaluative index.

BHA is used to define specific natural elements in window views and to measure the richness of landscape elements. Biophilic design is a design concept aimed at integrating nature and natural elements into the built environment to create spaces that promote human health and well-being. This study follows Kellert's theory [31], and extracts seven common spatial elements in window views: water features, plants, natural landscapes or ecosystems, nature-mimicking art, natural materials, natural colors, and signs of weathering or mottling. The more elements present in a window view, the higher its biophilic element richness.

OLD refers to the median distance of the green landscape visible from a window to the observer [32]. Typically, distant window views are considered more acceptable, open, and of higher quality. Therefore, to describe the nature of green window views more accurately, this study supplements the measurement of the distance from the observer to the green landscape as a parameter to describe the visibility of greenery.

To meet the requirements of typical window views, virtual residential models are established, and panoramic images with 15 combinations of five window view elements are rendered in high (High), middle (Middle), and low (Low) richness levels. The images maintain consistent interior spaces, varying only in window view elements (Figure 1). To eliminate the psychological and physiological impacts of the virtual environment itself, participants view a baseline panoramic environment of a room without windows in a virtual reality setting. Each typical scenario is set with only the corresponding single measurement index as the independent variable, keeping other measurement indices consistent in the images.

2.2 Experiment design

To ensure adequate statistical power for detecting the effects of different temperature groups on environmental emotion and thermal perception, this study adopted an effect size of 0.347, as recommended by Yao et al. [33], aiming for a significance level of 0.05 and a power of 0.8, yielding a minimum required sample size of 22 participants. Consequently, the experiment included 24 participants, comprising 7 males and 17 females.

Participants were asked to arrive in the laboratory at least 30 minutes before the experiment for thermal acclimatization. The actual experimental environment was set in a 4m x 5m north-facing enclosed, no-window laboratory. The room temperature and humidity were continuously monitored using a HOBO UX100-003 sensor, ensuring a deviation of $\leqslant 0.5^\circ$ C. Uniform clothing insulation (clo) was set at 1.0. To highlight the differences between the control and experimental groups and to explore whether green window views could expand the comfortable temperature range for energy-saving purposes, two sets of borderline climate conditions, not meeting but close to the ASHRAE Standard 55-2017 requirements, were chosen. The laboratory setup is shown in Figure 2. Participants were distributed into two groups, with similar age, gender, and body size distribution in each group.

(a) The low-temperature group's environment was controlled at 19.3℃ (±0.5℃) with a humidity of 45% (±3%), PMV (Predicted Mean Vote) =-1.09, PPD (Predicted Percentage of Dissatisfied) =30%, the thermal sensation was "Slightly Cool", and SET (Standard Effective Temperature) =21.8 °C. This group consisted of 4 males and 8 females, totaling 12 participants with an average age of 24.419±1.327.

(b) The high-temperature group's environment was maintained at 25.3℃ (±0.5℃) with a humidity of 45% (±3%), PMV=0.51, PPD=11%, the thermal sensation was "Slightly Warm", and SET=27.5 ° C. This group consisted of 3 males and 9 females, totaling 12 participants with an average age of 25.167±1.347.

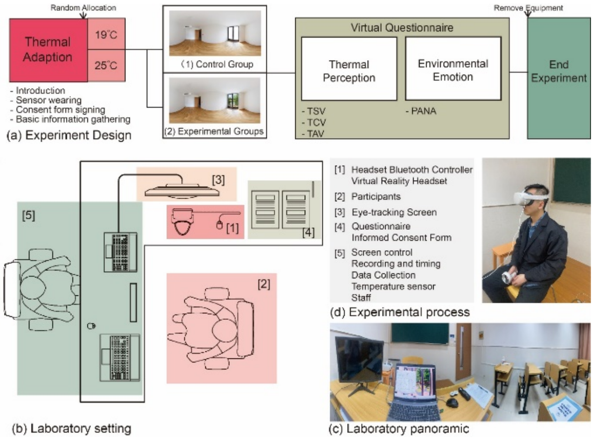

Fig. 2. Experiment Design.

After preparation, participants were required to view randomly played virtual scenes through VR equipment, each for 30 seconds. After the immersive experience, while still wearing the headset, participants used a controller to answer questionnaires on thermal perception and psychological assessments displayed on the virtual platform. This process was repeated until evaluations of all 15 experimental scenes and the control scene were completed.

2.3 Questionnaire design

Before the experiment started, demographic information was collected to control the inter-group differences. Referencing other studies on visual-thermal interaction, a questionnaire was designed to measure each scene. The questions include:

(a) Thermal Perception: The construction of the thermal perception scale is based on two major international thermal comfort standards: the European Union's EN ISO 7730:2005 and the ASHRAE Standard 55-2021. This scale includes questions on thermal sensation, thermal comfort, and thermal acceptance. The Thermal Sensation Vote (TSV) aligns with the PMV. Thermal comfort vote (TCV) is rated on a 7-point scale, ranging from very uncomfortable (1) to very comfortable (7). Thermal acceptance vote (TAV) is adapted from the Thermal Acceptance Ratio (TAR), a 100-point rating scale, used to help subjects distinguish minor comfort differences between similar scenes.

(b) Environmental Emotion: This utilizes the Positive and Negative Affect Schedule (PANA) emotion model [34], which categorizes emotions into eight types based on arousal and pleasure levels, accurately delineating the relationships between different emotions and defining their positions. This model is the most common emotional evaluation model in visual-thermal interaction research. It can more accurately define the details of emotions, thereby inferring what kind of emotional arousal is caused by the window view, which leads to the thermal perception of participants under visual stimulation changes [35].

3 Results

3.1 Impact of green view elements on thermal perception

With the gradual increase in the SVF (Table 1), the thermal sensation votes follow a U-shaped curve. According to participant reports, this might be because the SVF-M scenarios evoke associations with windy environments, thereby shifting thermal sensation votes towards the cooler end and increasing thermal comfort due to a shift towards neutrality. Thermal comfort scores are highest in the SVF-M group, with little difference between the SVF-L and SVF-H groups. The thermal evaluation scores show minor differences across groups. Excluding the unique modeling effect of the SVF-M group, in general, an increase in SVF leads to a shift of thermal sensation votes towards the warmer end, while the changes in thermal comfort and evaluation depend on the environmental temperature conditions experienced by the participants.

The increase in the VGI leads to a decrease in thermal sensation scores among participants in the high-temperature group and an increase in the low-temperature group, aligning the thermal sensation scores of both groups more towards neutrality. Moreover, it significantly improves thermal comfort and evaluation.

With the gradual increase in CR, the thermal sensation votes show a rising trend in both temperature groups, suggesting that participants perceive environments with higher color richness as warmer. However, the scores for thermal comfort and thermal evaluation slightly decrease with increasing CR.

As the richness of BHA increases, the thermal sensation scores in both temperature groups exhibit a U-shaped trend. According to participants' reports, this could be due to the prevalence of dark concrete and other dark artificial materials in BHA-L scenes, which evoke associations with the high temperatures of asphalt and concrete surfaces in summer. The scores for thermal comfort and thermal evaluation noticeably increase with the enhancement of BHA.

As the OLD progressively increases, the thermal sensation votes also rise, indicating that a greater landscape distance makes participants feel warmer. Compared to other green visibility factors, OLD has a less significant impact on thermal comfort and acceptance, with similar scores across the three groups.

Table 1. Average and standard deviation of results for different temperature groups.

Group (Mean ± Standard Deviation)						
	19°C(n=192)		**25°C(n=192)**		**F**	**p**
TSV	0.23±1.03		0.41±0.99		3.232	0.073
TCV	4.74±1.23		4.65±1.22		0.544	0.461
TAV	78.27±10.07		73.67±12.80		15.268	0.000**
	TSV		**TCV**		**TAV**	
	25°C	**19°C**	**25°C**	**19°C**	**25°C**	**19°C**
Control Group	0.67±0.89	-0.08±0.90	3.92±0.90	4.17±1.11	60.42±14.37	64.83±16.02
SVF-L	0.58±1.24	0.17±1.27	4.83±1.19	5.00±1.04	76.83±12.06	80.67±6.91
SVF-M	0.17±1.03	0.33±0.89	5.33±0.89	5.33±1.07	79.33±11.89	80.92±7.84
SVF-H	0.50±1.45	0.42±1.00	4.67±1.37	5.25±1.14	78.33±11.54	83.42±8.20
VGI-L	0.25±0.62	0.20±0.92	4.75±1.14	4.80±1.03	73.67±10.56	78.40±5.70
VGI-M	0.33±0.78	0.00±0.95	5.25±1.36	5.00±1.04	76.08±13.08	79.50±7.34
VGI-H	0.08±0.79	0.31±0.75	5.58±0.90	5.69±1.32	80.00±9.76	84.69±8.65
CR-L	0.58±0.79	0.17±1.11	4.67±1.23	4.83±1.27	74.17±13.18	80.00±7.06
CR-M	0.92±0.79	0.58±1.16	4.50±1.17	4.75±1.14	72.67±12.64	79.08±8.31
CR-H	1.17±0.94	0.83±1.11	4.25±1.29	4.83±0.94	72.17±14.43	79.08±9.39
BHA-L	0.17±1.03	-0.08±1.44	3.33±1.37	3.08±1.16	64.17±14.75	67.58±12.18
BHA-M	0.00±1.13	-0.33±0.65	5.08±1.08	4.67±1.15	75.08±11.56	79.83±7.65
BHA-H	0.08±1.16	0.25±0.87	4.83±1.11	5.25±0.87	75.58±12.72	82.17±6.56
OLD-L	0.33±0.78	0.00±1.04	4.42±1.08	4.42±1.16	73.08±11.18	78.33±8.86
OLD-M	0.33±1.07	0.25±1.22	4.58±0.79	4.25±1.22	75.67±8.97	77.08±10.14
OLD-H	0.42±0.90	0.58±1.00	4.33±1.23	4.42±1.16	71.42±12.30	76.17±8.48
F	1.245	0.965	2.789	3.517	2.089	3.977
p	0.243	0.494	0.001**	0.000**	0.012*	0.000**
* p<0.05 ** p<0.01; F=F-statistic; p= p-value						

3.2 Environmental emotion and thermal perception

Within the same set of scenes, environmental emotion, and thermal perception exhibit the same correlation. The way participants interpret environmental characteristics (as "cold" or "hot") also impacts their thermal perception. Emotion dimensions that are "warm," such as satisfaction, are associated with positive thermal comfort and thermal acceptance evaluations, as well as a sensation of warmth. Conversely, "cold" emotional dimensions, such as quietness, correlate with negative thermal comfort and thermal acceptance evaluations, as well as a sensation of coldness. Temperature also influences how participants interpret the emotional tone of the same scene. In the low-temperature group, a shift in the measurement of environmental emotions from "warm" to "cold" can be observed. In lower ambient temperatures, participants are inclined to perceive the scene as quieter, sadder, or more painful. (Table 2)

Table 2. Environmental emotion and thermal perception correlation analysis.

Group	19℃			25℃		
Emotion	**TSV**	**TCV**	**TAV**	**TSV**	**TCV**	**TAV**
Satisfaction	0.283**	0.522**	0.474**	0.135	0.541**	0.345**
Restfulness	-0.046	0.412**	0.414**	-0.099	0.493**	0.323**
Quietness	-0.257**	-0.078	0.036	-0.300**	0.117	0.098
Stillness	-0.045	-0.439**	-0.301**	-0.076	-0.447**	-0.258**
Sadness	-0.177*	-0.271**	-0.207**	-0.061	-0.325**	-0.178*
Pain	0.062	-0.298**	-0.243**	0.115	-0.218**	-0.182*
Excitement	0.228**	-0.117	0.014	0.334**	-0.026	0.053
Positivity	0.186**	0.159*	0.240**	0.261**	0.178*	0.225**
*** p<0.05 ** p<0.01**						

4 Discussion

4.1 Hypothesis 1: The visibility elements of greenery in window views can influence participants' thermal perception

Different elements of green visibility have varying impacts on residents' thermal perception. Biophilic Design Attributes enhance thermal comfort and evaluation scores, suggesting their increased incorporation in design. The increase in Color Richness does not necessarily improve thermal comfort and evaluation scores; it might even lead to a decline in environmental and thermal evaluations. Observer Landscape Distance has a minimal impact on thermal perception and need not be a primary consideration in window view design. An increase in the Visible Green Index tends to neutralize thermal sensation scores and significantly enhances thermal comfort and evaluation, advocating for the use of more greenery and three-dimensional greening strategies in design to raise VGI. The increase in the Sky View Factor shifts thermal sensation votes towards the warmer end, while changes in thermal comfort and evaluation depend on the ambient temperature experienced by participants. For application, architects can create different color richness in different seasons by creating a landscape that changes with the four seasons or a diverse mix of plants. In summer, using more cool colors or single colors to reduce the feeling of heat, and in autumn and winter, more warm colors or multi-colors to enhance the feeling of warmth. Planting on the exterior walls and roofs of buildings can increase VGI and BHA, which can not only improve the urban climate and environment (Tang et al., 2023) but also improve indoor thermal perception.

4.2 Hypothesis 2: Emotional tendencies towards window view elements can affect indoor thermal perception in residential settings

Thermal sensation is significantly positively correlated with emotional dimensions, this correlation holds across different temperature groups and scene groups, indicating a bidirectional effect. Not only does temperature influence participants' emotional evaluations of the environment, but the way participants interpret environmental characteristics (as "cold" or "hot") also impacts their thermal perception. In other words, scenes with an emotionally "cold" tone make people feel "cold" in terms of thermal sensation, and colder environments, people are more likely to perceive environmental emotions as cold; the same applies to hot. Using this finding, architects can configure window elements and warm colors with positive emotional associations in winter to enhance the emotional evaluation of the residential living environment and also make residents feel that the environment is hotter; the opposite is true in summer.

5 Conclusion

Through controlled experimentation, this study validated the relationships between five green visibility indices and three thermal perception indices, thereby testing two hypotheses and further exploring which elements of green window views could impact thermal perception. This study confirms that some green visibility elements are associated with positive thermal perception, such as BHA and VGI. Others depend on the environmental temperature, like SVF and CR, while OLD shows no significant correlation. The result also shows that positive emotional dimensions correlate with improved thermal perception. This can provide a reference for future sustainable and energy-efficient design of residential window views and outdoor environments. For constructions and renovations, by integrating these findings with other residential environmental enhancement strategies, the built environment can mitigate thermal discomfort among residents in suboptimal thermal conditions, indirectly reducing air conditioning energy consumption. Future studies could expand the sample size and demographic diversity, including more green visibility scenes and real-world feedback validation.

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