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Combined effects of the visual-thermal environment on restorative benefits in hot outdoor public spaces: A case study in Shenzhen, China

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ABSTRACT

In the context of global warming and rapid urbanisation, improving visual-thermal environments in public spaces is key to enhancing well-being in high-density cities. This study utilizes deep learning techniques and field measurements to quantify visual and thermal environment factors. It examines the contribution of influencing factors in different green view spaces and reveals how to modulate multisensory experience through visual factors under specific thermal environments to promote recovery benefits. The result shows that thermal factors play a significant role, with solar radiation being the most important factor affecting restoration in low green view index spaces (GVI < 30 %). Furthermore, the study revealed that high orderliness could alleviate thermal discomfort (solar radiation > 600W/m^2) and promote overall restoration. Additionally, under calm or light air conditions (wind speed < 1.5 m/s), enhancing landscape depth can facilitate restoration in spaces with high GVI. Our research allows for a deeper understanding of the potential value of the combined effects of visual-thermal environments in enhancing residents' health under intensified heat exposure. It also provides important implications for how limited greening resources can be used effectively to maximise their restorative benefits in high-density cities.

1. Introduction

Prolonged exposure to urban environments has been shown to induce psychological stress and mental fatigue, adversely affecting human health and leading to a high incidence of stress-related illnesses such as anxiety, psychiatric disorders, and cardiovascular diseases [1–3]. Consequently, the provision of restorative spaces within urban areas has become increasingly important and urgent [3,4]. Research on restorative environments is guided by two primary theories: Attention Restoration Theory (ART) and Stress Recovery Theory (SRT) [5,6]. Both theories propose that exposure to environments with certain characteristics can facilitate recovery from attentional fatigue and emotional distress and improve individual psychological well-being. While earlier studies primarily focused on the restorative effects of traditional blue and green therapeutic spaces, there is an increasing need on everyday accessible public spaces within cities due to the rapid transformation of urban land and the highly fragmented spatial patterns [7–11].

However, rapid urbanization has led to significant changes in the visual and thermal environments of cities, posing serious challenges to the creation of restorative outdoor public spaces. From a thermal environment perspective, urban expansion and its impact on global climate change have intensified both the extent and scale of urban heat island effects [12–15]. The high proportion of impervious surfaces and tall building facades in cities contributes to elevated urban temperatures and reduced wind speeds, increasing the likelihood of residents' exposure to thermally uncomfortable conditions [16–19]. Existing study has demonstrated a significant relationship between air temperature, relative humidity, and physiological stress responses [20]. Furthermore, microclimatic benefits such as providing shading and humidity on streets have been proven to alleviate residents' mental stress [21]. A study conducted in hot regions revealed that thermal perception significantly predicts the psychological restorative effects of urban spaces [16]. These findings suggest that thermally uncomfortable environments adversely affect residents' overall health. From a visual environment perspective, urban public spaces, designed to meet high-intensity and multifunctional use demands, have increasingly incorporated more hard surfaces and artificial infrastructure, making it difficult to fully achieve the traditional restorative conditions associated

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with high levels of greening [8,11,22,23].

Relying on a single sensory dimension alone may be insufficient in addressing the wide range of challenges posed by urbanization [24,25], and the combined effects of multisensory environments are recognized as a crucial intervention for enhancing the restorative benefits [26–28]. In urban settings, individuals are more likely to be influenced by multisensory stimuli rather than isolated sensory inputs due to the complex combination of elements [8,29,30]. According to Gestalt theory, multisensory inputs from the environment are not simply the additive sum of individual sensory signals but function as an integrated whole through composite effects [31,32]. Specific sensory stimuli could mitigate discomfort in another sensory dimension and thereby enhance the restorative experience. For instance, Lee et al. found that despite the lack of visually engaging features in certain urban spaces, the soft tactile experience of grass could act as a compensatory mechanism and provide a pleasant experience [33]. Additionally, vertical greening and well-maintained building facades have been shown to consistently mitigate attentional fatigue and psychological stress, counteracting the adverse effects of environmental noise exposure on mental health [34,35]. Research also suggested that the aesthetic qualities and aromatic scents of plants can alleviate discomfort associated with high summer temperatures in outdoor spaces, thereby enhancing restorative benefits [21,28]. Furthermore, multisensory environments could influence the overall perception through either additive effects or masking effects. For instance, Pitt demonstrated that whole-body tactility with plant textures, combined with visual aesthetics, could jointly contribute to an immersive experience with attention and stress recovery [36]. Ba and Kang noted that the introduction of urban traffic noise could mask olfactory factors, thereby diminishing overall perception [37]. Despite the growing body of research on multisensory dimensions of restoration, existing studies primarily focus on visual, olfactory, and auditory environments, with few studies discussing the impact of integrated visual-thermal environments on restorative benefits.

In the context of intensified heat exposure, the combined effects of visual and thermal environments have a more pronounced impact on perception than other sensory interactions [38–40]. Elsadek et al. found that cherry blossom trees with relatively low sky view factor (SVF) can provide a restorative experience as powerful as that of high-shade vegetation [21]. Lam et al. indicated that enhancing visual comfort can mitigate discomfort from hot outdoor environments [41]. Seyedrezaei explored the interactions between lighting Correlated Color Temperature (CCT) and temperature, suggesting that a warmer lighting color can improve selective attention capabilities in warm thermal settings [42]. In addition, one research indicated that higher Universal Thermal Climate Index (UTCI) values could improve subjective comfort under low outdoor illumination and a another study revealed a significant association between the interaction of UTCI conditions and aesthetic vote on overall comfort [40,43]. However, in existing studies on integrated visual-thermal environments, visual factors are often limited to lower-level features (such as illuminance and color) or rely on subjective vote. However, these studies lack visual metrics related to spatial elements and configurational characteristics supported by landscape design principles.

In reviewing these studies, we draw two key observations. Firstly, while it is widely accepted that higher green view levels are beneficial for restoration, there remains a gap in exploring how to enhance restorative benefits in urban areas with varying levels of greening due to the objective reality of differential green coverage in public spaces amid urbanization. Secondly, within the context of intensified outdoor heat exposure, systematic research on the combined effects of visual and thermal environments is lacking, along with a need for scientifically quantifiable indicators at the objective design level to support practical applications in landscape design.

To bridge these gaps, we integrated deep learning and field measurement methods to explore how the combined effects of visual and thermal environments can maximize the restorative potential with varying greening levels in hot public spaces. Specifically, this research aims to address the following questions: (1) Under different green view levels, which key factors in the visual and thermal environments significantly influence restorative benefits, and how does the characteristic contribution of these factors vary with changes in green view levels? (2) Under specific thermal conditions, how can visual configurational factors (such as landscape depth, orderliness, and permeability, etc.) be employed to modulate multisensory experiences and enhance restorative benefits?

This study contributes to the development of methods and knowledge mainly in three ways. (1) In response to the challenges of global climate change, we propose strategies based on the combined effect of multisensory environments, offering an alternative to traditional physical methods of modifying thermal environments. (2) Against the backdrop of accelerating urbanization, we explore how to effectively utilize limited urban green spaces to maximize their health and well-being benefits, with potential applicability to other high-density cities. (3) By employing deep learning to extract and calculate visual spatial attributes and configurational characteristics, this study provides reliable and objective metrics to support urban spatial design practices.

2. Methodology

2.1. Site selection

Shenzhen (22.5°′N, 114°′E) , located in the southern part of Guangdong Province, is one of the most important metropolises in China. It was selected as the study site for two reasons. Firstly, it has a subtropical monsoon climate, with an annual average temperature of 23.3 °C and an average of 1853 h of sunshine per year, making it an ideal hot place to carry out the research [44]. Secondly, as a typical high-density city in China with highly intensive urban land use, Shenzhen could offer valuable practical insights for other high-density cities on enhancing restorative performance under limited greening conditions [45].

Forty-four sites in three public spaces accessible for daily use by urban residents in the central urban area of Shenzhen were selected (Fig. 1). These spaces feature a rich variety of visual and thermal environmental characteristics, with each containing hard surfaces. The experimental sites were spatially categorized based on green view index (GVI), totaling 15 low-green-view spaces (GVI $<$ 30 %), 16 medium-green-view spaces (30 %$\leq$GVI$\leq$60 %) and 13 high-green-view spaces (GVI$>$60 %). The Green View Index (GVI) is an indicator that measures the degree of visible green elements in a specific scene, which are commonly used to explore the relationship between environmental greening and human health [46,47]. It is calculated by capturing panoramic images from the central point of each location and applying semantic segmentation to determine the proportion of green elements (trees, shrubs, and grass, etc.) in the images.

2.2. Participants

Forty healthy adult participants were recruited for each park, with an average age of 25 $\pm$ 6 years and a gender ratio of 1:1. All participants were instructed to avoid any stimulants (such as caffeine and nicotine) and to maintain normal eating and sleeping habits within the 24 h prior to the experiment to eliminate external factors that might potentially affect cognitive performance. To control for uniform thermal exposure, participants were required to wear short-sleeved shirts and lightweight pants [39]. Recruitment was conducted through online emails and WeChat groups (a Chinese social media platform), with the research team disseminating a detailed advertisement describing the study's purpose and procedures to student groups. Informed consent was obtained from all participants before the experiment. This study adhered to the ethical guidelines of Harbin Institute of Technology.

Fig. 1. Locations of 44 sites were selected in 3 public spaces in Shenzhen, China.

2.3. Experimental design

The outdoor experiments were conducted from 8.00 to 10.00 a.m. and 2.00–5.00 p.m. in September, with sunny conditions and no rainfall. The average temperature on the experiment days was 32.48 °C, with a humidity of 73.3 %. September was chosen as the experimental month for two main reasons: First, Shenzhen's summer climate spans from April to November [48], and temperatures in September are representative of the common thermal conditions in hot cities [44]. Second, the study excluded the extreme heat of July and August to avoid the potential masking effect of intense thermal stress on other sensory perceptions [40,49].

2.4. Assessments of restorative benefits

Restorative benefits refer to the enhancement of an individual's physiological, psychological, or cognitive functions after exposure to specific environments, such as stress reduction, attention restoration, or improved mental clarity. The restorative outcome scale (ROS) was utilized to measure participants' perceived restoration, which is a validated and reliable tool that has demonstrated good usability in previous studies (Appendix) [21,50,51]. The ROS questionnaire consists of six items. Three of the items reflected relaxation and calmness (e.g. "I feel calmer after being here"), one item reflected attention restoration ("my concentration and alertness clearly increase here") and two items reflected clearing one's thoughts (e.g. "I can forget everyday worries here"). Each rated by participants on a seven-point Likert scale ranging from "1–not at all" to "7–completely" and the final restorative outcome was determined by calculating the average score of the six items.

Participants were divided into groups of 2–4 to avoid congestion at each experimental location [21]. Upon arrival, they engaged in a 10-minute rest period, during which the experimenter explained the procedure and instructions. Participants then completed a basic information questionnaire (including gender, age, and education level) and the ROS questionnaire. Each group proceeded to the experimental location for a 5-minute environmental perception session, a duration that has been demonstrated in previous studies to be sufficient for inducing restorative effects [52–54]. Subsequently, participants completed the ROS questionnaire. After a 5-minute break, participants moved to the next location guided by the experimenter and repeated the same procedure.

2.5. Assessment of thermal environmental factors

Four commonly used thermal environmental factors in architecture were selected for the outdoor experiment: air temperature, relative humidity, wind speed, and solar radiation [55–58]. A handheld TH-PQX5 weather station was used to measure air temperature, relative humidity, and wind speed, while a SM206-Solar power meter was used for solar radiation measurement. Measurements were taken at a height of 1.5 m to reflect the thermal environment as perceived by the human body [59]. During the experiment, a researcher was responsible for holding the instruments and recording microclimate data at each location with samples taken every 20 s, which aligns with the response time

Table 1
The characteristics of the Measuring Instruments for thermal environment.

Thermal environmental factors	Instruments	Range	Precision	Picture
Air temperature	TH-PQX5 weather station	−40 °C-85 °C	±0.3 °C	
Relative humidity	TH-PQX5 portable weather station	0–100 %	±1 %RH	
Wind speed	TH-PQX5 portable weather station	0–40m/s	±0.3m/s	
Solar radiation	SM206-Solar power meter	0.1–1999.9w/m^2	± (10 %*R* + 2dgt)	

of the TH-PQX5 portable weather station. The specific characteristics of the Measuring Instruments are shown in Table 1.

2.6. Selection and quantification of visual environmental factors

The visual factors are divided into two categories: visual spatial attributes and visual configurational characteristics [60]. Spatial attributes refer to the types of elements and their physical characteristics, such as density, material, and color, etc. [61,62]. Specific indicators include the leisure facility density, vegetation diversity, ground interface diversity, and surrounding building density. Existing research has demonstrated that features like seating areas and playgrounds in urban spaces can enhance restoration by increasing landscape fascination and compatibility, which are recognized as the restorative qualities based on Attention Restoration Theory (ART) [11,63]. Building density reflects the visual impact of dense urban development on public space perception; when the sky view is obstructed by surrounding buildings, it may induce a sense of pressure [35]. Moreover, complex plant communities and enriched interfaces enhance visual complexity, which engage effortless bottom-up attention and allow the mind to wander and reflect [6,64,65].

Configurational characteristics refers to the arrangement of elements within a setting, including enclosure, permeability, landscape depth and orderliness [60,66]. Enclosure refers to the degree to which physical boundaries define the spatial extent, impacting perceptions of openness and activity limitations. Permeability refers to the extent to which one's line of sight can extend through a space without obstruction, and environments with high visual permeability were proved to capture people's attention and alleviate stress [67,68]. Higher landscape depth creates a more layered and engaging view, which can promote psychological restoration by fostering a richer perceptual experience as indicated in Stress Recovery Theory (SRT) [69–71]. Orderliness represents the regularity and coherence of element arrangements, which could effectively capture people's attention and reduce cognitive load [6,66,72].

To evaluate the visual quality of the experimental scenes, images were captured at the center of each experimental point. The camera height was set to 1.6 m to simulate a pedestrian's perspective and images were taken to capture the site's front view, left view, right view, top interface, and ground interface. The SegFormer semantic segmentation model, trained on the ADE20 K image dataset, was used for semantic segmentation, allowing the extraction of landscape element types and their respective proportions, thus providing the basis for subsequent indicator calculations. A fully convolutional residual network (FCRN) was applied for monocular depth estimation, enabling the determination of foreground, midground, and background layers, as well as landscape depth values (Fig. 2). Image-based metrics has proved to be effective to assess the visual quality [22,73]. The final visual indicators and calculation method are shown in Table 2.

2.7. Statistical analysis

First, Bartlett's test was applied to compare the distribution of restorative benefits and thermal conditions across different green view spaces. Then, correlation analysis was conducted to identify visual and thermal environmental factors associated with restoration at various levels of green view spaces. Next, a Random Forest (RF) model was applied to analyze the feature contributions of these influencing factors. Finally, analysis of variance (ANOVA) was performed, followed by Tukey's Honestly Significant Difference (HSD) test for multiple group comparisons, to assess whether significant differences exist in visual environmental factors across various thermal conditions.

RF is an ensemble learning algorithm that relies on randomized decision trees to assess the importance of each explanatory variable [74]. In this study, the conditional permutation variable importance method was employed to determine the feature importance of thermal and visual environmental factors using RF. An 80 % training set and a 20 % test set were used for training. During the training phase, three key parameters were tuned to optimize the RF model: (1) Number of Trees (n_{trees}) : This parameter determines the number of decision trees in the RF. A larger number of trees can enhance model stability and accuracy. (2) Minimum number of samples per leaf node ($n_{\text{min\_leaf}}$) : This controls the minimum number of samples required at each leaf node, helping to prevent overfitting. (3) Maximum Number of Splits ($n_{\text{max\_splits}}$) : This sets the maximum number of feature splits per tree, regulating tree depth. After training, predictions were made using the feature matrix X_{test} of the test set to obtain the predicted labels$\hat{y}_{\text{test}}$. Model performance was assessed by calculating the coefficient of determination, R^2. Finally, the model's feature importance was evaluated using the "Out-of-Bag Error" (OOB Error), calculated by assessing the error of each decision tree on samples not included in its training set.

Bartlett's Test is a statistical method used to examine whether the variances of multiple groups are equal, primarily aimed at verifying whether there are significant differences in variances among groups.

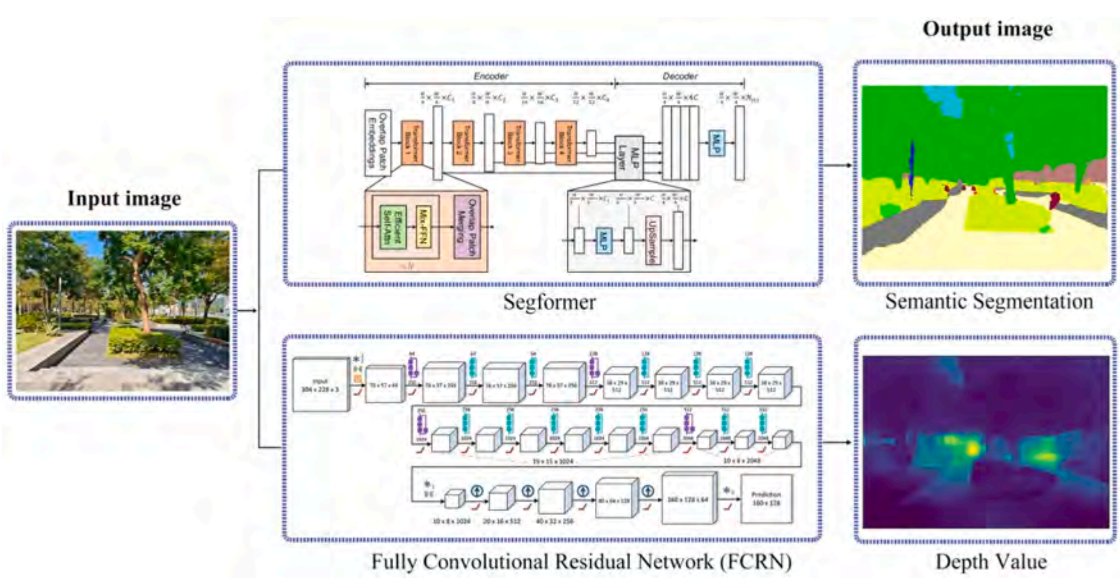

Fig. 2. Semantic segmentation and deep value computation based on deep learning.

Table 2
Indicators and calculation methods for visual environment.

Indicator	Descriptions	Calculation Method
Visual Spatial Attributes		
Leisure Facility Density	Proportion of leisure facilities used for rest, entertainment, or social interaction in the site.	Sum of the area proportions of leisure facility (bench, sculptures, and pitch, etc.) in the image.
Vegetation Community Diversity	Richness of different plant species in the site.	Shannon diversity index H=-$\sum$[(pi) × ln(pi)] p_i is the area proportion of the ith species (tree, grass plant and palm).
Ground Interface Diversity	The variation of multiple elements on or near the ground surface in the site.	Simpson Diversity Index $D = 1-\sum(\mathrm{pi})^2$ p_i is the area proportion of the ith elements (grass, sand, road, stairs, water body, etc.) on the ground.
Surrounding Building Density	Proportion of surrounding buildings visible within the site.	Sum of the area proportions of buildings in the background layers of the image.
Visual Configurational Characteristics		
Permeability	The range visible to the human eye when looking outward from the site.	Sum of the area proportions of visually unobstructed elements (road, path, sidewalk, sky, grass, water, etc.) in the image.
Enclosure	The degree to which a space is physically enclosed by boundaries or objects.	Sum of the area proportions of enclosing elements (tree, plant, wall, building, fence, railing, column, signboard, etc.) in the foreground and midground layers of the image.
Landscape Depth	Visual depth perception or spatial layering from the observer's viewpoint to the distant end of the landscape.	Distance of objects to the viewpoint in the image.
Orderliness	The degree of unity and visual order achieved through the repetitive patterns of scene components.	Sum of the area proportions of orderly repetitive elements in the image.

HSD test is a post-hoc analysis used to identify significant differences in mean scores between assessment points. This is achieved through pairwise comparisons of mean values across all assessment points while maintaining control over the overall Type I error rate. This test is particularly useful for providing a clear view of significant differences when comparing multiple groups. In this study, The RF model was conducted using Matrix Laboratory (MATLAB). All other statistical analysis was conducted using SPSS 25.0 (IBM Corporation, NY, USA). The significance level was set at $p < 0.05$.

3. Results

3.1. Comparative analysis of three types spaces with different green view index

Bartlett's test (Table 3) was applied to compare the distribution of restorative benefits and thermal conditions (air temperature, relative humidity, wind speed, and solar radiation) across low green view spaces (GVI<30 %), medium green view spaces (30 %≤GVI≤60 %) and high green view spaces (GVI>60 %). The normality of each group was verified using the Shapiro-Wilk test, and all data were confirmed to meet the assumptions of Bartlett's test. The results indicate a p-value of 0.034 for restorative benefits at a significance level of 0.05, demonstrating significant differences in the variances of restorative scores among the spaces. Further post-hoc analysis (Table 4) was conducted to explore specific pairwise differences, revealing that the restorative effects in medium and high green view spaces are significantly higher than those in low green view spaces, while the difference between medium and high green view spaces is negligible. Although previous studies focusing solely on visual aspects have suggested a positive correlation between green view levels and restoration, our findings demonstrate that other factors also play a crucial role, indicating that restoration are not entirely dominated by greenery levels [75,76]. In terms of thermal conditions, the p-value was less than 0.01, indicating significant differences in temperature among the varying greening spaces. The restorative effects in low green view spaces are significantly higher than those in medium and high green view spaces, which can be attributed to the cooling effects of vegetation [77,75]. Additionally, the p-values for relative humidity, wind speed, and solar radiation in Bartlett's test were all greater than 0.05, indicating no significant differences across the three green view spaces.

3.2. Visual and thermal factors related to restoration in different green view spaces

Fig. 3 shows the correlation analysis between environmental factors and perceived restoration in low green view (GVI<30 %) spaces. In terms of thermal environmental factors, air temperature (r=−0.337,$p <$ 0.01) and solar radiation (r=−0.295, $p < 0.01$) exhibit a significant negative correlation with perceived restoration, while wind speed and relative humidity show no correlation with restoration. For visual spatial attributes, leisure facility density ($r = 0.200$, $p < 0.01$), vegetation diversity ($r = 0.125$, $p < 0.01$), and ground interface diversity ($r =$ 0.133, $p < 0.01$), are found to be associated with perceived restoration. Furthermore, in terms of visual configurational characteristics, perceived restoration has a strong positive correlation with permeability ($r = 0.151$, $p < 0.01$) and is also positively correlated with average depth ($r = 0.097$, $p < 0.05$) and orderliness ($r = 0.179$, $p < 0.01$).

Fig. 4 shows the correlation analysis between environmental factors and perceived restorative benefits in medium green view (30 %≤ GVI≤60 %) spaces. The results indicate that perceived restoration is negatively correlated with both air temperature (r=−0.354, $p < 0.01$) and solar radiation (r=−0.276, $p < 0.01$), positively correlated with wind speed ($r = 0.182$, $p < 0.01$), and shows no correlation with relative humidity (r=−0.065, $p > 0.05$). Similar to findings in low green view spaces, ground interface diversity ($r = 0.118$, $p < 0.01$), vegetation diversity ($r = 0.086$, $p < 0.05$), and permeability ($r = 0.088$, $p < 0.05$) are significant factors associated with restoration. Enclosure ($r = 0.094$, $p <$ 0.05) also has a positive correlation with restoration, suggesting that spaces with clearly defined boundaries are preferred for perceived restoration, aligning with the concept of "extent" in the ART [6,78,79]. Additionally, surrounding building density (r=−0.133, $p < 0.01$) is negatively correlated with restoration, a finding consistent with previous studies suggesting that high-density urban environments contribute

Table 3
Comparative analysis for different green view spaces based on Bartlett's test.

Restorative benefits		Thermal conditions			
		Air temperature	Relative humidity	Wind speed	Solar radiation
P-value	0.034	0.000	0.438	0.521	0.515

Table 4
Post-hoc analysis of different green view spaces in restorative benefits and thermal conditions.

Variable	Types of Space	Types of Space	Standardized Mean Difference	T-Statistic	*P*-Value
Restorative benefits	Low green view spaces	Medium green view spaces	−0.315	−5.091	0.000
	Low green view spaces	High green view spaces	−0.221	−3.286	0.001
	Medium green view spaces	High green view spaces	0.106	1.655	0.098
Air temperature	Low green view spaces	Medium green view spaces	0.490	7.867	0.000
	Low green view spaces	High green view spaces	0.578	8.625	0.000
	Medium green view spaces	High green view spaces	0.086	1.333	0.182

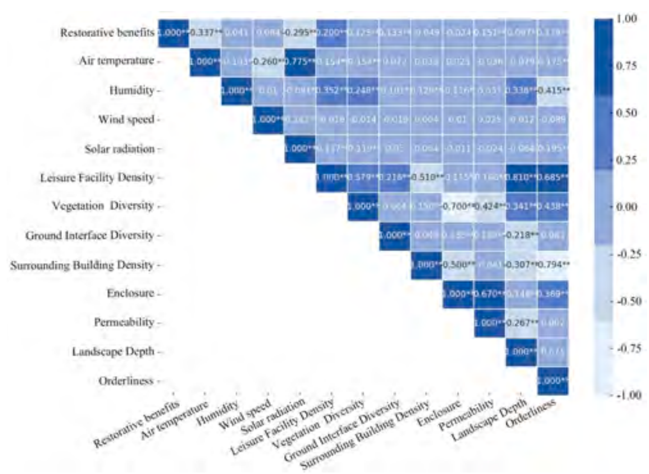

Fig. 3. Visual and thermal factors related to restoration in low green view spaces (* Significant at the 95 % level, p < 0.05; ** Significant at the 99 % level, p < 0.01).

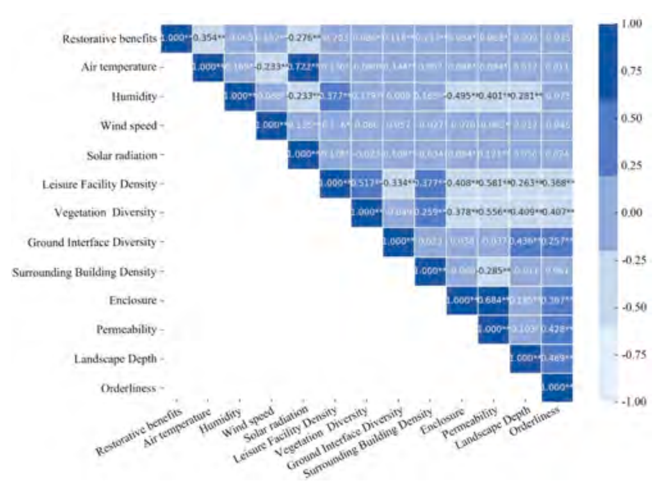

Fig. 4. Visual and thermal factors related to restoration in medium green view spaces (* Significant at the 95 % level, p < 0.05; ** Significant at the 99 % level, p < 0.01).

to a sense of stress.

Fig. 5 shows the correlation analysis between environmental factors and perceived restorative benefits in high green view (GVI>60 %) spaces. From the perspective of thermal environmental factors, air temperature (r=−0.224, p < 0.01), wind speed (r = 0.112, p < 0.05), and solar radiation (r=−0.243, p < 0.01) are correlated with perceived restorative benefits, similar to findings of medium green view spaces. In terms of visual spatial attributes, leisure facility density (r = 0.184, p < 0.05) and ground interface diversity (r = 0.135, p < 0.01) also show a positive correlation with restoration. Additionally, surrounding building density (r = 0.203, p < 0.01) is positively correlated with restoration,

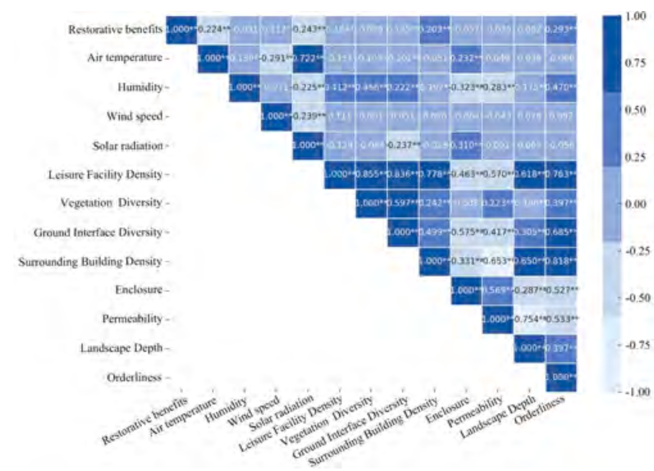

Fig. 5. Visual and thermal factors related to restoration in high green view spaces (* Significant at the 95 % level, p < 0.05; ** Significant at the 99 % level, p < 0.01).

which contrasts with the findings in medium green view spaces. Regarding visual configurational characteristics, orderliness (r = 0.293, p < 0.01) is the only factor associated with perceived restoration. High-greening-level environments with complex visual information may increase cognitive load, and the role of orderliness can be explained by ART, which suggests that it reduces visual clutter and enhances coherence by providing clear structures for elements [6,78,79].

3.3. Feature importance of explanatory variables

The Feature Importance based on the RF model measures the contribution weights of visual and thermal environmental factors related to restorative benefits. Model analyses were conducted separately for spaces with three levels of green view index, yielding R^2 values of 72 %, 67 %, and 65 %, respectively. In studies involving complex environmental factors and human psychological perceptions, where the aim is to explain relationships between variables rather than prediction accuracy, an R^2 level above 60 % has been demonstrated to provide strong explanatory power [80–82]. The final results are shown in Figs. 6. The larger the value of conditional permutation variable importance, the more significant the corresponding environmental factor.

According to the results in Fig. 6(a), in low green view spaces, solar radiation has the largest impact on restoration, followed by air temperature and permeability, with leisure facility density having the smallest effect. The results in Fig. 6(b) indicate that in medium green view spaces, air temperature is the most significant contributing factor, with solar radiation and enclosure also having notable impacts. Based on Fig. 6(c), in high green view spaces, wind speed has the greatest influence, followed by solar radiation and surrounding building density. Overall, thermal factors contribute across spaces with all three green view spaces. The impact of ground interface diversity is less pronounced in medium and high green view spaces compared to low green view spaces.

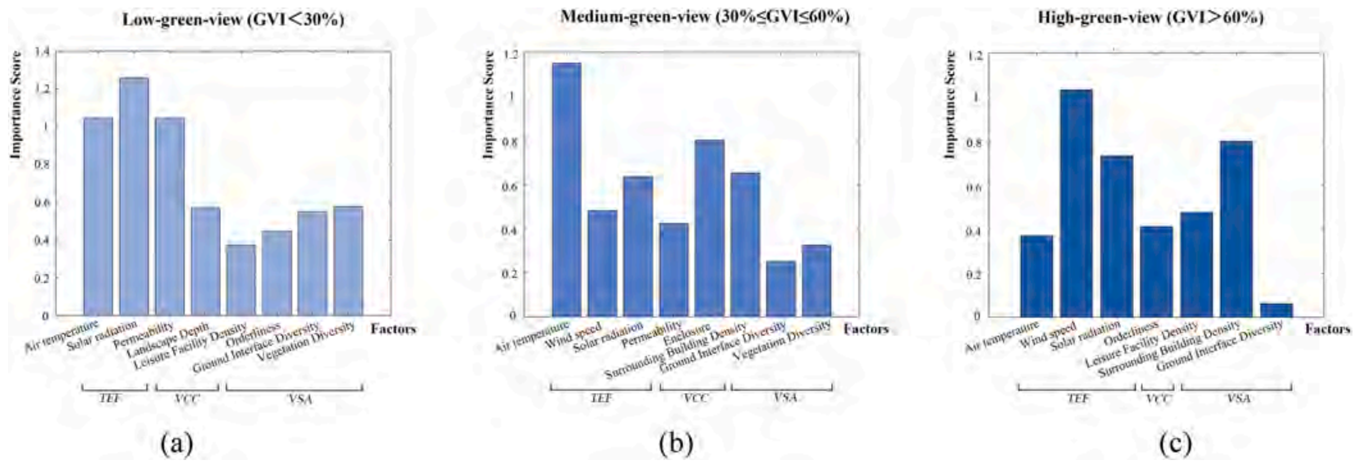

Fig. 6. Contribution weights of visual and thermal environmental factors in different green view spaces (TEF: Thermal Environmental Factors; VCC: Visual Configurational Characteristics; VSA: Visual Spatial Attributes).

3.4. Comparison of visual environments across different thermal conditions

To facilitate a more intuitive interpretation of spatial characteristics for design guidance, the visual configurational characteristics have been simplified into three levels: low, medium, and high. Thermal environmental factors have also been classified based on commonly standards and field observations into three categories: air temperature (<31 °C, 31–33 °C, >33 °C), wind speed (<1 m/s, 1–3 m/s, >3 m/s), and solar radiation (<300 W/m^2, 300–600 W/m^2, >600 W/m^2) [83]. Variance analysis and Tukey's Honestly Significant Difference (HSD) test were used for multiple comparisons between groups to systematically assess which visual environments are more conducive to restorative benefits under different thermal conditions. Table 3–5 presents the effect of visual factors on restoration under different thermal conditions based on ANOVA. Fig. 7–9 presents the results of the HSD test with these significant groups, detailing the differences for each relevant comparison.

Table 5 and Fig. 7 present the results for spaces with low Green View spaces (GVI<30 %) . In terms of air temperature, spaces with more permeable visual configurational characteristics show significant restorative effects when the temperature is below 31 °C ($p < 0.01$). Regarding wind speed, when wind speed is less than 3.3 m/s, high permeability significantly improves restorative effects compared to medium permeability ($p < 0.01$). Additionally, when wind speed is below 1.5 m/s, medium landscape depth shows significantly better restorative effects than low landscape depth ($p < 0.05$). In terms of solar radiation, the effects of different visual characteristic groups on restorative benefits were not significant. This indicates that no visual factors were found to enhance restorative effects under specific solar radiation conditions.

Table 6 and Fig. 8 present the results for spaces with medium green view spaces (30 % ≤ GVI ≤ 60 %). No significant differences in means scores were observed in different air temperature conditions, indicating the absence of visual characteristic factors that could improve restorative effects under specific temperature conditions. The differences in mean scores across groups under different temperature conditions are not significant, indicating the absence of visual characteristic factors that could improve restorative effects under specific temperature conditions. Regarding wind speed, when the wind speed exceeds 3.3 m/s, spaces with high enclosure show a significant mean difference from other spaces ($p < 0.01$). When wind speed is below 3.3 m/s, no significant difference in mean scores is observed across groups. Regarding solar radiation, spaces with high landscape depth ($p < 0.05$) and orderliness ($p < 0.05$) show a significant restorative effect when the solar radiation exceeds 600 W/m^2 under high solar radiation conditions (> 600 W/m^2). This finding suggests that enhancing landscape layering and orderliness can alleviate thermal discomfort and improve restorative outcomes.

Table 7 and Fig. 9 present the results for spaces with high green view spaces (GVI > 60 %). Under different temperature conditions, the mean score differences among the groups were not significant, which is consistent with medium green view spaces. In addition, when wind speed is below 1.5 m/s, there is a significant difference in mean scores between the high average depth group and the medium depth group ($p < 0.05$). when wind speed is between 1.5–3.3 m/s, the difference between the medium depth group and the low depth group is also observed ($p < 0.05$). This suggests that higher average depth has a significant effect in promoting restorative benefits under no-wind or light air conditions. When solar radiation exceeds 600 W/m^2, there were significant mean differences in orderliness ($p < 0.01$) and enclosure ($p < 0.01$). No effect of different visual characteristic groups on restoration were observed when solar radiation is below 300 W/m^2.

Table 5
Effect of visual factors on restoration under different thermal conditions in low-view-spaces (*P*-values) .

		Permeability	Enclosure	Landscape Depth	Orderliness
Air temperature	<31 °C	p<0.01	0.98	0.215	0.305
	31–33 °C	0.058	0.834	0.405	0.631
	>33 °C	0.066	0.38	0.123	0.893
Wind speed	<1 m/s	p<0.01	0.22	p<0.05	0.977
	1–3.3 m/s	p<0.01	0.462	0.321	0.286
	>3 .3m/s	0.065	0.29	0.582	0.864
Solar radiation	<300 W/m^2	0.456	0.375	0.315	0.787
	300–600 W/m^2	0.103	0.943	0.447	0.122
	>600 W/m^2	0.209	0.357	0.548	0.39

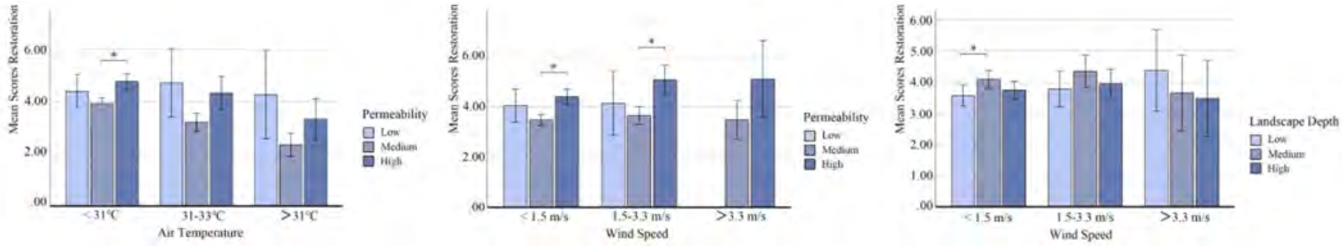

Fig. 7. The Tukey post-hoc test results for the groups with significant effects in ANOVA in low green view spaces.

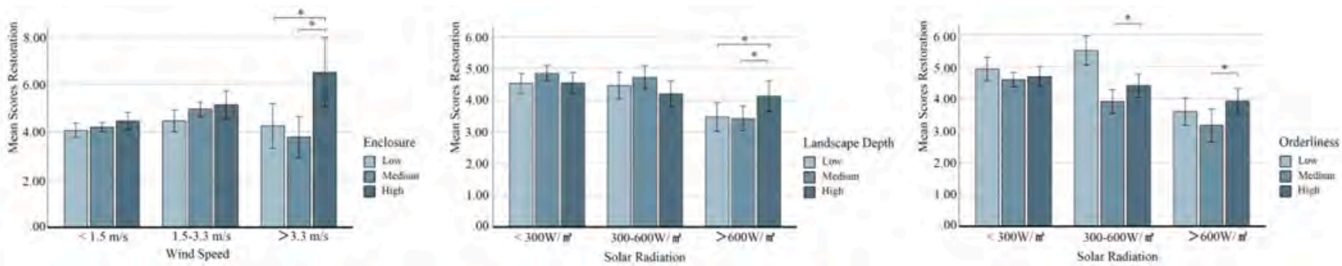

Fig. 8. The Tukey post-hoc test results for the groups with significant effects in ANOVA in medium green view spaces.

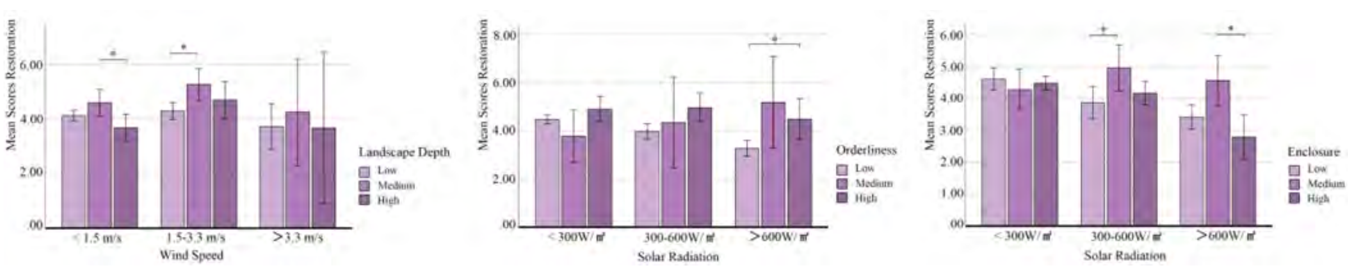

Fig. 9. The Tukey post-hoc test results for the groups with significant effects in ANOVA in high green view spaces.

Table 6
Effect of visual factors on restoration under different thermal conditions in medium-view-spaces (*P*-values).

		Permeability	Enclosure	Landscape Depth	Orderliness
Air temperature	<31 °C	0.27	0.31	0.24	0.23
	31–33 °C	0.695	0.844	0.791	0.68
	>33 °C	0.408	0.58	0.549	0.24
Wind speed	<1 m/s	0.267	0.267	0.486	0.356
	1–3.3 m/s	0.122	0.122	0.341	0.055
	>3.3 m/s	0.066	p<0.01	0.216	0.263
Solar radiation	<300 W/m^2	0.309	0.638	0.184	0.324
	300–600 W/m^2	0.12	0.051	0.185	p<0.01
	>600 W/m^2	0.067	0.229	p<0.05	p<0.05

Table 7
Effect of visual factors on restoration under different thermal conditions in high-view-spaces (*P*-values).

		Permeability	Enclosure	Landscape Depth	Orderliness
Air temperature	<31 °C	0.318	0.34	0.32	0.064
	31–33 °C	0.335	0.637	0.928	0.747
	>33 °C	0.623	0.341	0.584	0.134
Wind speed	<1 m/s	0.345	0.595	p<0.05	0.146
	1–3 .3m/s	0.267	0.109	p<0.05	0.061
	>3 .3m/s	0.533	0.975	0.883	0.620
Solar radiation	<300 W/m^2	0.456	0.638	0.292	0.138
	300–600 W/m^2	0.103	0.051	0.258	p<0.01
	>600 W/m^2	0.209	p<0.01	0.076	p<0.01

4. Discussion

4.1. The comprehensive impact of visual and thermal environments on restoration under different green view index levels

Our study investigates the visual and thermal environmental factors associated with restorative benefits in green view spaces ranging from low to high, evaluating their respective contributions to the restoration. Furthermore, we conduct a comparative analysis of the combined effects of visual and thermal factors in different greenery levels to reveal both their consistencies and distinctive characteristics.

Our study found that air temperature, wind speed, and solar radiation are significantly correlated with restorative effects across spaces with varying levels of greenery, apart from wind speed, which showed no significant correlation in low green view index spaces. This finding confirms the necessity of incorporating thermal factors into restorative studies and aligns with current research conclusions in hot outdoor spaces [16,20]. Compared to previous studies, our research further reveals that sunlight, temperature, and wind speed are the most critical restorative factors for low, medium, and high greenery spaces, respectively. This finding offers valuable insights for prioritizing enhancements in restorative performance across different types of green spaces. In addition, we also found that ground interface diversity is the only visual factor that shows a significant correlation across spaces with all levels of greenery.

At low green view spaces (GVI $<$ 30 %), solar radiation is the most significant factor contributing to restorative benefits. This finding suggests that providing artificial shading facilities to block solar radiation is the most critical approach for enhancing restorative benefits with low greenery. While previous studies have promoted recovery through other sensory experiences such as tactile and olfactory with limited visual environment, our study provides valuable insights from other dimension, which is particularly relevant for hot cities [28,33]. In addition, visual permeability is the second most important factor influencing restoration, as be supported by existing research, which suggests that increasing exposure to the sky and everyday activities can enhance perceptual experience [67,84]. This finding provides guidance for design strategies, suggesting that in environments with limited greenery, enhancing sky visibility and establishing horizontal connections with adjacent spaces can contribute to restoration.

In environments with moderate levels of greenery (30 % $\leq$ GVI $\leq$ 60 %), air temperature emerges as the primary factor contributing to restorative benefits, with enclosure as the second most influential, followed by solar radiation and surrounding building density. Our study suggests that these spaces favor a design approach that balances enclosure with visual permeability, indicating that while plant walls formed by dense vegetation offer effective shelter, they are not well-suited for these spaces; instead, it is essential to create a more visually permeable view. Additionally, the observed negative impact of surrounding building density on restoration aligns with previous findings, which suggest that heavily obstructed views due to surrounding buildings can elicit feelings of stress [35].

At high green view spaces (GVI $>$ 60 %), wind speed becomes the most critical factor in enhancing restorative benefits, indicating that increasing wind speed is an effective approach for promoting restoration in these spaces. Solar radiation and surrounding building density are the following contributing factors. An interesting finding is that, in high green-view environments, surrounding building density shows a positive correlation with restoration, which is in complete contrast to its effect at moderate greenery levels. One possible explanation is that the combination of high-density buildings and abundant greenery offers richer visual stimulation, as Ulrich proposed that diverse landscape elements could promote perception with a more enriched visual experience [85]. This finding suggests that surrounding buildings are not always negative elements in urban environments; In fact, strategically arranging building density and greenery levels could achieve a balance between urban development and public health.

4.2. The effects of visual environments on promoting restorative benefits under specific thermal conditions

Another key contribution of our research is the further elucidation of how the visual environment can enhance overall restorative experiences under different thermal conditions, particularly in high-air temperature, low-wind speed, and high-solar radiation conditions that negatively impact thermal perception in hot outdoor spaces. Previous studies align with our findings, suggesting that improvements in users' visual comfort can increase their tolerance to thermal conditions and thus facilitate a more positive overall perceptual experience [38,86–88]. However, compared to previous studies that primarily focused on subjective evaluations of the visual environment, our research focus on objective visual configurational characteristics, providing the implementable solutions to support practical design in addressing thermal exposure environments.

Landscape depth and orderliness can alleviate discomfort caused by high solar radiation, thereby promoting overall restoration. Specifically, When the green view index exceeds 30 %, spaces with high orderliness demonstrate significant restorative effects when solar radiation exceeds 600 W/m^2. Previous studies support this finding, suggesting that orderly environments could provide a sense of coherence and reduce visual clutter, which in turn alleviates mental fatigue and enhances tolerance to external heat stress [89]. When the green view index is between 30 % and 60 %, spaces with high landscape depth also exhibit significant restorative benefits under high solar radiation conditions. However, it is important to note that when the green view index is below 30 %, no visual configurational factors were found to mitigate solar radiation discomfort. Overall, in contrast to previous studies that focus on reducing solar radiation intensity from the physical methods, our study offers a new strategy through the combined effects of multisensory.

Landscape depth and enclosure can each promote restorative benefits under low and high wind speed conditions, respectively. Specifically, when the green view index exceeds 60 %, spaces with high average depth effectively enhance restoration under calm or light air conditions (when wind speed $<$ 1.5 m/s). Additionally, when the green view index is between 30 % and 60 %, our findings indicate that spaces with high enclosure can effectively promote restoration when the wind speed exceeds 3.3m/s.

When air temperatures exceed 33 °C, no visual factors significantly enhance restorative effects. Previous studies support our findings, noting that a poor performance in one sensory factor may mask the effects of other factors in multisensory interactions [90]. This suggests that the combined effects of visual and thermal environments may lose effectiveness beyond a specific threshold. Therefore, it is essential to account for optimal levels of sensory interactions, enabling policy-makers and planners to select appropriate intervention stages that maximize restorative benefits while avoiding resource wastage.

4.3. Expansion of the existing theoretical framework and application strategies

Our study expands the existing theoretical framework in three key aspects. First, the study extends traditional restorative theories represented by ART and SRT, highlighting that restorative benefits are influenced not only by visual factors but also significantly by thermal factors [5,6]. Second, it introduces quantifiable visual metrics based on deep learning techniques, overcoming the previous reliance on subjective perception and providing a more scientific and practical foundation for design applications [40,43]. Finally, the study underscores the importance of context-specific adaptations, emphasizing the need for tailored environmental configuration strategies under varying greenery and thermal conditions to effectively enhance residents' health and well-being.

The findings could provide practical strategies for public spaces with varying levels of urban greenery. Specifically, in low green view spaces, providing artificial shading facilities such as canopies or shaded structures is a key approach to enhancing restorative benefits, as solar radiation is the primary factor influencing restoration. In medium green view spaces, restorative benefits can be maximized by creating spatial enclosures aligned with natural wind directions to form wind corridor effects. This approach combines high wind speeds with visual enclosure to achieve optimal restorative outcomes. In high green view spaces, increasing wind flow can promote restoration. Additionally, restoration can still be supported under low wind speed conditions. In cases where dense vegetation blocks airflow, urban designers might consider compensating by arranging multi-layered vegetation or alternating near and distant landscape structures to enhance overall restoration. Furthermore, in medium to high green view spaces, enhancing spatial orderliness can alleviate the thermal discomfort caused by intense solar radiation.

4.4. Limitations and further research

As with most studies, this study also has its limitations. First, using a sample of college students may not represent other age groups. Future studies could expand the sample to include a wider range of the population and incorporate comparisons between different cultural groups [91]. Secondly, although visual and thermal factors are the main influences in hot urban environments, other sensory factors such as olfactory and auditory stimuli also influence perceptual experience [28, 92]. Future studies could further investigate multisensory interactions with more sensory dimensions. Finally, similar to previous studies, research on restorative environments has mainly examined short-term effects [93]. Future studies could explore the dynamic effects of thermal environmental changes on restoration over longer periods of time.

Nevertheless, our research contributes to a more comprehensive understanding of how the combined effects of visual and thermal environments can effectively promote restoration across spaces with varying levels of greenery. Compared to previous studies that primarily improve thermal environments through physical methods, this study offers new insights into alleviating thermal discomfort and enhancing restorative benefits through the integrated effects of multisensory. Overall, this study has important applications for improving the well-being with limited urban green space resources in the context of high-density development and increasing heat exposure.

5. Conclusion

This study aims to explore how to enhance the restorative benefits of public spaces through the combined effects of visual and thermal environments under climate challenges such as global warming and the urban heat island effect. Outdoor experiments were conducted in Shenzhen in September, with 44 points categorized into low, medium, and high greenery spaces (GVI). Measuring instruments and the perceived restoration questionnaire were used to assess thermal environmental factors and restorative benefits, respectively. Visual environments were documented through field photography and subsequently quantified using the Segformer semantic segmentation model and the FCRN depth calculation model. Our study reveals the combined effects of visual and thermal environmental factors on restoration benefits under different greening conditions, and further explores the effects of visual configurational factors, such as landscape depth, orderliness, and enclosure, on the improvement of restoration in specific thermal environments.

The study's findings indicate that: (1) Air temperature, solar radiation, and ground interface diversity are consistently associated with spaces across greenery levels from low to high. Additionally, solar radiation, air temperature, and wind speed are the most critical restorative factors affecting low, medium, and high spaces, respectively. (2) When the green view index (GVI) exceeds 30 %, spaces with high spatial order can alleviate discomfort caused by intense solar radiation, thereby enhancing overall restorative benefits. (3) In spaces with GVI between 30 % and 60 %, high enclosure levels significantly improve restorative benefits when wind speeds exceed 3.3 m/s. (4) When GVI exceeds 60 %, spaces with high landscape depth effectively promote restoration in the calm or light air conditions (wind speed $<$1.5 m/s). (5) When the air temperature exceeds 33 °C, no visual factors significantly improve restorative effects. Understanding the combined effects of visual-thermal environments not only provides practical insights for future urban planning, enabling the effective use of limited greenery resources to maximize restorative benefits, but also offers innovative health-oriented design strategies to address global climate change and rapid urbanization.

CRediT authorship contribution statement

Wen DONG: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Donghui DAI:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition. **Mei LIU:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Yaowu WANG:** Writing – review & editing, Project administration, Formal analysis. **Shuang LI:** Software, Investigation. **Pengyuan SHEN:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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