Spatial Optimization Strategies for High Temperature Heat Exposure Based on Thermally Vulnerable Populations and Case Studies

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Abstract The objective of this study is to investigate the factors that contribute to brittleness and to identify strategies for mitigating these factors in populations with varying degrees of thermal vulnerability, based on the potential impact of extreme heat exposure on human survival and habitability. The physiological condition of lower adaptability to high temperature environments and the assessment of individuals who may have higher tolerance time in high temperature environments based on spatial perspectives suggest the need for targeted spatial optimization strategies for commuters and disadvantaged populations. This is demonstrated through a case study. These optimization measures encompass a variety of aspects, including the integration of transportation systems, the expansion of grey space corridors, the improvement of green space layout, and the implantation of green infrastructure. The study aims to reduce the exposure time of thermally vulnerable individuals to high temperature environments through spatial optimization strategies, to enhance the resilience of urban green spaces to heat stress, and to reduce the probability of heat-wave occurrence.

Keywords Thermal vulnerability, Exposure, High temperature environment, Spatial optimization

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According to projections by the United Nations, the global population will increase from 7.7 billion to 9.7 billion between 2019 and 2050. Concurrently, the number of people living in cities will grow by approximately 72%, with the urban population reaching 6.3 billion and the global urbanization rate reaching 65%[1]. The phenomenon of high-speed urbanization also gives rise to the urban heat island effect, which has a direct or indirect negative impact on the health of urban residents. This is evidenced by the association between high temperatures and an increased incidence of cardiovascular and cerebrovascular diseases, respiratory illnesses, as well as the occurrence of heat-related illnesses and deaths directly caused by high temperatures. This is particularly evident in high temperature heat exposure spaces within urban areas. It is well established that high temperature heat waves present a significant risk to the health of urban residents, with those with lower heat tolerance being particularly vulnerable.

In their study, Sherwood and Huber employed a physiologically based approach to assess future heat stress risk. They utilized the relationship between thermal environments and health outcomes, considering human energy balance. Their findings indicated that a 35 °C wet bulb temperature (T_w) threshold would result in death after 6 h of exposure. However, it is important to note that the 6 h survival limit for T_w varies depending on the magnitude of the mean radiant temperature (T_a) and relative humidity (RH). For instance, healthy young individuals can withstand T_w conditions of 33.6 °C, while in dry conditions they can only withstand T_w conditions of 32.3 °C[2].

The IPCC acknowledges that extreme weather and climate hazards are the consequence of a confluence of extreme events and the exposure and vulnerability of human and natural systems. In response, the IPCC has proposed

Column introduction

The phenomenon of high-speed urbanization has been identified as a significant contributor to the urban heat island effect. This study proposes targeted spatial optimization strategies for commuters and disadvantaged individuals based on an analysis of the influencing factors of high temperature heat exposure spaces. The objective is to enhance the accessibility and comfort of urban green spaces in the context of high temperature heat exposure, thereby alleviating the heat stress of disadvantaged individuals.

The objective of the City Observer column is to observe the cities in which we live, to reveal the essence behind the surface, and to identify the source of vitality. We will continue to disseminate the findings of our ongoing global city observation initiative and provide insights into the events unfolding in urban settings from a professional standpoint.

Yang Xin, Zhang Qi, the hosts of RLncut research station

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a framework for evaluating disaster risk based on the three dimensions of hazard, exposure, and vulnerability[3]. In high temperature thermal extreme environments, hazards are defined as factors external to the system that may present a threat to the system. These factors are largely uncontrollable, such as geographic climate, temperature, and altitude. The term "exposure" is used to describe a range of factors that affect surface temperature, including population density, environmental functions, ground albedo, infrastructure, and other variables. These factors can have both direct and indirect effects on temperature. Vulnerability is defined as the propensity or tendency to be adversely affected, which can be categorized as sensitivity and adaptive capacity. It reflects the degree of susceptibility of the affected body to natural hazards[3]. This study should consider individual body characteristics and physiological impairments, as well as interventions to modify or reduce the impact of heat exposure on the body, including lowering the metabolic rate and reducing exposure behaviors. This is essential for optimizing space for heat exposure to high temperatures.

1 Characteristics and influencing factors of high temperature heat exposure space

The influences on high temperature heat exposure space can be summarized in two main aspects: climatic and spatial factors. Climatic factors are uncontrollable and consist mainly of high temperature stress climatic characteristics, such as the number of high temperature days, the intensity of high temperatures, and the frequency and duration of heat waves. The climatic features in question exert a direct influence on changes in ambient temperature, and as a consequence, they have a significant impact on the severity and duration of heat stress events. In contrast, spatial factors are controllable and encompass spatial influences in hot and hot climates. These factors encompass the type of surface cover, the urban heat island effect, population density, vegetation cover, and underpass coverage. By regulating these spatial factors, it is possible to influence the thermal environment of high temperature exposure spaces to a certain extent, thus mitigating the effects of high temperature stress on the human body and the environment.

1.1 Climate characteristics of high temperature stress

High temperature stress is a natural phenomenon that refers to a prolonged period of time when the ambient temperature is higher than the human comfort level. This can have adverse effects on human health and ecosystems. Scholars have identified several key indicators that reflect the severity and duration of heat events in heat-stressed climates (Table 1). The number of high temperature days provides an indication of the frequency of high temperature events. High temperature intensity is a measure of the severity of high temperatures. Heat-wave frequency is a measure of the number of consecutive occurrences of high temperature events. Heat-wave duration describes the length of time that a high temperature event lasts. The duration of a high temperature event can be determined by examining the length of time that temperatures remain elevated. The intensity of a heat wave, on the other hand, is defined as the height of temperatures during a high temperature event. By combining these metrics, it is possible to gain a more comprehensive understanding of the magnitude of high temperature stress impacts and to formulate appropriate precautionary measures.

1.2 Impact factors of heat exposure space

The impact factors of heat exposure space can be categorized into two distinct categories: direct and indirect (Table 2). Direct impacts are those factors that have a direct impact on the measurement of the hazard of heat exposure space. The confluence of elevated summer temperatures and the urban heat island effect serves to amplify the impact of heat on the human body. In addition to air temperature, surface temperature is primarily influenced by surface radiation. The absorption and reflectance of solar radiation by different types of land cover vary considerably. For instance, impervious surface paving exhibits lower reflectance and absorbance than permeable floor tiles. This is positively correlated with surface temperature, which makes it easier for residents in the area to be exposed to the thermal environment. Furthermore, the urban heat island effect serves to prolong the duration of high temperatures and to increase the probability that residents will be exposed to hot environments to some extent[4]. Population density and normalized vegetation index (NVI) are among the principal indicators of the urban heat island effect. The higher the normalized vegetation index, the lower the urban heat island effect. Humidity also exerts a certain influence on the urban heat island effect. Research simulations have demonstrated that at high temperatures, human beings have a higher survivability in high humidity environments compared with low humidity environments. Subways, as the most utilized underground corridors by city dwellers, can effectively reduce the exposure of daytime commuters to the heat in summer. The indirect impacts of climate change are due to external social resources that reduce the amount of time people spend in hot environments. Green parks are effective in regulating the microclimate of the region and are the main places for nearby residents to cool off in the summer. Transportation stations meet the needs of commuters for a short break from the summer heat. Community service centers have some medical equipment to provide timely treatment for those who are exposed to the hazards of high temperatures. These indicators assess the population's accessibility to social resources.

2 Brittleness factors of thermally vulnerable populations

The concept of vulnerability was initially introduced in the field of natural hazards, initially referring to the degree to which a system is subjected to irresistible damage and impacts[5]. Since then, it has been progressively applied to disciplines such as climate, socio-economy, and others. Thermal vulnerability is defined as the degree to which urban systems or populations are susceptible to, or incapable of coping with, the adverse impacts of hot weather as a result of the combined effects of the heat island effect and hot weather[6]. Vescovi et al.[7] employed the degree of crowd sensitivity and the intensity of high temperature hazards as a guideline layer. This study utilized the street as a unit to investigate the factors influencing individual thermal vulnerability. It analyzed the factors causing brittleness (Table 3), identified high temperature-sensitive populations, and proposed spatial improvement strategies for high temperature heat exposure spaces.

The thermal sensitivity of different individuals exhibits different spatial adaptations and tolerance times for high temperature heat exposure. This study focuses on those who may be exposed to high temperature heat exposure for extended periods of time and helps to identify targeted protective measures and adaptation programs. It has been demonstrated that the elderly are the most susceptible to the health effects of heat waves due to their heightened sensitivity to hot environments and greater potential for exposure to such conditions[8]. This is attributed to their physiological characteristics, which render them more vulnerable to heatstroke and its complications, particularly in the context of poor body conditioning or chronic illnesses. Additionally, females are also more sensitized to hot environments due to their physiological characteristics. Outdoor workers are particularly susceptible to heat stress and are more likely to be exposed to hot environments than others. Individual income and cognitive level influence the capacity of individuals to utilize their own resources to cope with hot environments. Studies have demonstrated that the risk of death in hot environments is significantly higher in lowincome than in high-income groups[9].

3 Optimization strategy of high temperature heat exposure space

3.1 Reducing high temperature space withstand time—optimized traffic ex-perience for commuters

3.1.1 Integrating the transportation system to optimize the waiting experience. The optimization of urban transportation systems plays a pivotal role in the mitigation of the adverse effects of high temperature environments on users. One of the most effective strategies is the enhancement of the connectivity between various modes of transportation, including bus, subway, and cab stops, in order to provide more convenient travel options. The integrated transportation network enables residents to navigate the city in a more flexible manner, thereby reducing the time and cost associated with switching between transportation modes. For instance, the interconnection of bus stops and subway stations facilitates convenient transfers, thereby enhancing the efficiency of commuters' travel. Concurrently, the expansion of cab stands and shared bicycle parking spaces offers residents a greater degree of flexibility in their last-mile travel options, thereby further enhancing the overall convenience of the city's transportation system. The interconnectivity of various modes of transportation, as facilitated by this connectivity, serves to enhance the interconnectivity of urban transportation systems and to improve the operational efficiency of such systems.

Intelligent transportation systems can also provide commuters with significant convenience. Through intelligent transportation planning and management, the time spent by commuters on the road can be reduced, thus reducing the time they are exposed to the hot outdoors. For instance, the provision of real-time traffic information can assist commuters in avoiding congestion, reaching their destinations in a timely manner, selecting routes with tree cover, and reducing waiting and exposure time in hot weather. Furthermore, this integrated transportation network serves to mitigate urban traffic congestion and reduce traffic-related emissions, thereby conferring a net benefit on the urban environment and reducing the incidence of traffic accidents.

Case study: Graz main station local transportation hub—The Golden Eye. The principal transportation hub in Graz, Austria, is situated in the ground square of a vast, circular roof structure, locally designated as the "Golden Eye". The subterranean section encompasses four transportation lines, all of which are directly connected to the station. The cable car platform is situated in a semi-open area, and the hollow space above it permits the introduction of natural light and ventilation, thereby reducing the oppressive atmosphere experienced by waiting passengers (Fig.1). The most crucial element is an elliptical circular disk that encompasses the entire plaza, encompassing the station concourse and bus stops. This provides a circular, hot thermal space refuge. Furthermore, the plaza is linked to the bicycle path and offers bicycle parking. This design not only provides a comfortable waiting environment for passengers, but also provides a refuge for thermally vulnerable populations, reducing their exposure time in hot environments and protecting them from the adverse effects of the heat.

3.1.2 Creating green slow walkways and increasing gray space corridors. By identifying zones within the city with high accessibility but limited green infrastructure, it is possible to rationalize the planning of slow-moving trails suitable for commuting and recreation. These zones may include abandoned underpasses in the city, urban green space gaps, or spaces that are not easily utilized, such as under viaducts and urban fringe areas. These zones can be transformed into green, slow-walking trails through rational planning and design to provide a ventilated, cool, and comfortable resting place for commuters.

In the planning process, it is essential to consider the continuity and accessibility of the trails. This ensures that commuters can navigate the trails with ease and that suitable rest and recreational facilities, such as seating and resting kiosks, are provided. When planning

Table 1 Interpretation of high temperature indicators

No.	High temperature indicator	Indicator interpretation
1	Number of high temperature days	Number of days with daily maximum temperature ⩾ 36 °C
2	Heat-wave duration	Total number of days the heat wave process lasted
3	Heat-wave frequency	Number of consecutive occurrences of high temperature heat wave (⩾ 35 °C for 3 consecutive days)
4	High temperature intensity	Average of maximum temperatures on high temperature days (⩾ 35 °C)
5	Heat-wave intensity	Cumulative number of daily maximum temperatures that can exceed the high temperature threshold (35 °C) during a high temperature heat wave

Table 2 High temperature impact factors

Mode of impact	Impact factor	Relationships of impact
Direct	Surface temperature of high temperature hot time//°C	Positive
	Surface humidity of high temperature hot time//%	Positive
	Wind speed of high temperature hot time//m/s	Negative
	Normalized vegetation index	Negative
	Percentage of impervious surface pavement//%	Positive
	Population density//person/km²	Positive
Indirect	Area ratio of underground corridor//%	Negative
	10 min walking accessibility ratio of community service centers//%	Negative
	15 min walking accessibility ratio of public parks//%	Negative
	10 min walking accessibility ratio of transportation stations//%	Negative

Table 3 Brittleness factors of thermally vulnerable populations

No.	Impact factor	Relationships of impact
1	Proportion of resident female population//%	Negative
2	Proportion of resident population over 65 years of age//%	Negative
3	Proportion of resident population under 5 years of age//%	Negative
4	Proportion of resident population with chronic diseases//%	Negative
5	Proportion of population with less than a high school education//%	Negative
6	Proportion of occupations with permanent outdoor work//%	Negative
7	Proportion of population with low income (below 3,500 yuan)//%	Negative
8	Rent level per unit area//yuan/m²	Negative

green, slow-moving trails, it is also necessary to consider reasonable crosstalk with other modes of transportation in order to ensure the convenience of the trails. This implies that trails should complement the urban transportation system and become an integral part of the urban transportation network. In particular, the plan should consider the connection of the trail path with surrounding traffic arteries and public transportation stops. It should also address the installation of transportation facilities such as bicycle parking racks and bus stops. Furthermore, it should introduce an intelligent traffic management system to optimize traffic signal control. Finally, the plan should include the design of appealing landscaping and signage to enhance the recognition and attractiveness of the trail. The implementation of these measures will facilitate the seamless integration of green and slow-walking trails with the city's transportation system, thereby providing commuters with a convenient and comfortable travel experience.

Case study: The Green Mile—public space and streetscape design. The design team transformed an underutilized space under the flyover in Mumbai, India, a city with year-round temperatures above 20 °C, into a safe, vibrant public place that creates a positive and enjoyable neighborhood environment. This was achieved by creating pedestrian walkways and multiple tiny parks (Fig.2). The street upgrade resulted in the addition of 130 new trees and one acre of new public space beneath the overpass. The tree plantings extend throughout the space, providing green vegetation on both sides of the roadway. This vegetation has the potential to reduce air pollution, increase legibility, and provide an audio-visual buffer while lowering the temperature of the surrounding space.

This continuous public space serves as a conduit between the business district and the suburban train station. It houses five new modular open bus stops and cab bays, which integrate the surrounding traffic and prevent commuters from being exposed to the heat for extended periods. These "miniature green islands" are situated within a continuous space, comprising parks and plazas. They are furnished with seating, signage, and ample lighting, and are surrounded by landscaping elements such as depressions, islands, and trees. Their design is intended to provide shade and resilient spaces that can provide temporary shelter and buffers for thermally vulnerable populations. This design is of particular importance for Mumbai, situated in a region with high temperatures, as it provides a relatively cool passageway that effectively reduces discomfort during the hot season. This allows people to move more comfortably in the outdoor environment, enhancing the overall livability of the city.

3.2 Improving the thermal emergency response capacity of green spaces—targeting vulnerable people

The thermal emergency response capability of a green space is defined as the ability to mitigate heat-sensitive individuals in a given situation. In order to enhance this capability, it is necessary to consider a combination of factors, including experience, accessibility, and the mitigation of thermal responses. Firstly, the implementation of increased green vegetation coverage and the introduction of an appropriate quantity of water features can effectively reduce the surface temperature of green spaces, enhance comfort and attractiveness, and improve the willingness of individuals to enter green spaces. Secondly, the design of a reasonable layout of green space, including the provision of additional pocket parks and other small green spaces, is recommended to improve accessibility for the disadvantaged. Finally, the incorporation of water features and shading facilities serves to enhance the comfort of the green space and to alleviate the heat stress response, providing a quick and soothing effect.

3.2.1 Adding cooling element interactions. One strategy for improving body temperature in individuals is to increase cooling elements (Fig.3). Based on human perception, the impact of landscape on people can be categorized into three levels: visual, auditory, and sensory. For instance, the sight of ice on a hot summer day can evoke a sensation of cold, akin to the sight of a warm stove on a freezing day. It can be demonstrated that the utilization of cooling elements, such as water features and cool colors, in hot spaces can effectively enhance the perception of the hot space and induce a cool and refreshing sensation, which can subsequently reduce the perceived temperature of the environment and enhance the comfort of individuals in hot environments.

The introduction of water features, such as fountains, artificial lakes or streams, can result in a reduction in the temperature of the surrounding air. This is achieved through the evaporation of water and the reflection of the water surface. Furthermore, the presence of these features can also provide visual comfort and a sense of coolness. Additionally, the introduction of water features can facilitate the creation of a breeze effect, which can serve to further reduce the sensation of heat. In addition to the use of cool colors, such as blue, green, and purple, cool color design incorporates the use of light to enhance the effect of cool colors. This can be achieved through the use of soft blue light or green light to illuminate the building or landscape, thereby creating a cool atmosphere.

3.2.2 Improving accessibility to green space. Given the constraints on the maximum cooling distance and intensity of the green space, it is essential to guarantee the accessibility of the park's green space in order to optimize the cooling efficiency of the park, reduce the distance for the public to reach the green space, and enhance its cooling efficiency. The objective of enhancing accessibility to green space is achieved by optimizing the layout of pocket parks and improving the transportation network. Firstly, the optimization of the layout and design of pocket parks, with their placement in densely populated areas or on major traffic routes, will facilitate their accessibility to the public, thereby enhancing the ease of access to green space. The planning of pocket parks should consider the needs of the residents in the vicinity and provide a variety of recreational facilities and green landscaping to attract the public to engage in leisure activities. Secondly, the transportation network should be enhanced, including the implementation of additional walking and cycling paths to facilitate convenient transportation routes and reduce the distance for the public to reach the green space. The rational planning of roads and transportation hubs has resulted in the provision of multiple transportation options, which facilitate the public's access to the green space and enhance its accessibility. These initiatives will effectively promote the interaction between urban residents and green space, and enhance the utilization rate and sustainable development of urban green space.

3.2.3 Changing the layout of green spaces. The cooling efficiency of community parks is influenced by a multitude of factors (Fig.4), including their size, shape, location, and the presence of neighboring buildings[10]. The rational layout of green spaces can be employed to enhance the cooling effect of parks. The configuration of large, regularly shaped parks at the periphery of urban areas or in sparsely built-up zones, surrounded by low-rise and open buildings, is conducive to the enhancement of ventilation and heat dissipation within the parks, thereby providing a more comfortable outdoor recreational environment for the community. The following principles represent an ideal urban green infrastructure form design: the park should be located at the center of the neighborhood and

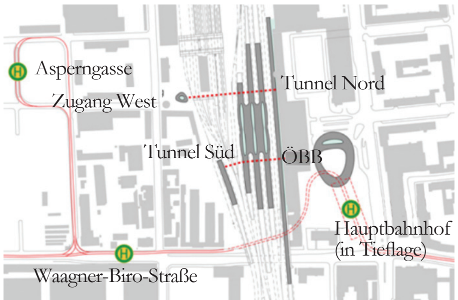

Fig.1 Traffic line plane

Fig.2 Space remodeling effect

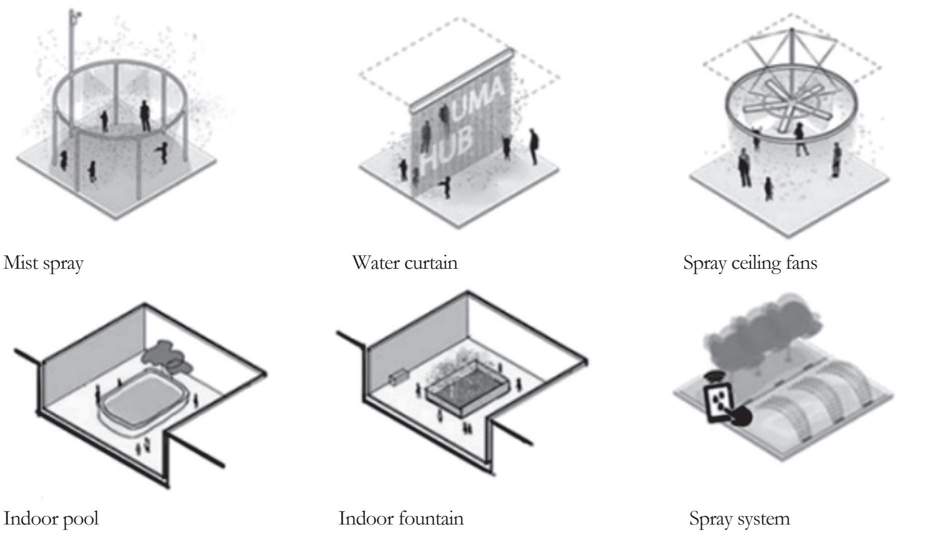

Fig.3 Implantation diagram of cooling elements

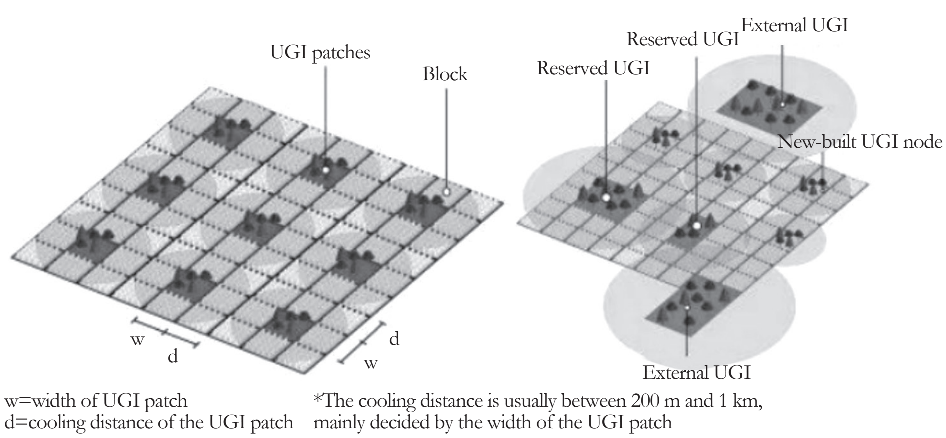

Fig.4 Ideal urban green infrastructure network that effectively cools neighboring urban areas

evenly distributed throughout the neighborhood; the park's shape should be increased in complexity while maintaining an appropriate minimum width; the park should be established in an upwind portion of the neighborhood; the park should be situated within the center of the neighborhood, with the surrounding area adjusted to reduce the height and density of buildings; the park should be at least 7.5 times as wide as the height of the surrounding buildings, and it should contain a body of water.

3.2.4 Increasing green infrastructure. Green infrastructure, including green belts, parks, wetlands, and water bodies, can be an effective means of reducing the temperature of the surrounding environment. These areas provide a cooler and more comfortable environment by maintaining relatively low air temperatures through the processes of evapotranspiration and shading, which are facilitated by the presence of vegetation. In a formal proposal, Yoji Aoki introduced the concept of green vision ratio (GVR). According to this concept, if the GVR is higher than 25%, people will perceive their surroundings as highly green. Conversely, if the GVR is higher than 50%, people will perceive the greenery as excellent and their comfort level with the environment will be significantly enhanced. The visibility of green spaces can be enhanced in two ways. ① Increasing green visibility on the plane: the plan entails the rationalization of the elimination of a portion of the travel lane and its conversion into a shared space for cafes and restaurants. The initiative encompasses the planting of new street trees to provide shade and seasonal landscaping, as well as the establishment of a green corridor of street trees running through the area. Additionally, the proportion of roof gardens should be increased. ② Increasing green visibility on the façade: it is recommended that the height of the planting pool should be increased and vertical greening should be installed. The spatial elements that can be seen and felt by humans, such as green appearance proportions, cooling materials, infrastructure, and artificial heat sources, are considered to be the most intuitive parts of a space that affect human senses.

Green infrastructure effectively reduces the duration of direct sunlight exposure, thereby lowering the temperature of the skin and body surfaces. This helps to slow the rate of increase in body temperature, reducing the discomfort of exposure to high temperatures and the associated health risks, such as heat stroke and sunburn. Additionally, it provides a relatively cool environment, which helps people to alleviate the discomfort associated with hot environments. Consequently, the establishment of green infrastructure in hot environments can alleviate the morbidity of heat-sensitive individuals in hot environments.

4 Conclusions

By examining the factors that cause brit-

(To be continued in P14)

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(Continued from P5)

tleness in populations that are vulnerable to thermal stress, we sought to identify strategies for enhancing the accessibility and comfort of urban green spaces in high temperature environments. This was done with the aim of alleviating the heat stress response of vulnerable populations. The study proposes a series of targeted strategies to enhance the accessibility and comfort of green spaces and thereby enhance the thermal emergency response capacity of vulnerable populations. These strategies include optimization of pocket parks and improvement of transportation networks. The integration of climatic and spatial factors is a key aspect of the study. In practice, the rational planning and design of green spaces can effectively improve the urban environment and enhance the quality of life for residents.

The study is of theoretical and practical significance for enhancing the accessibility and comfort of urban green spaces, mitigating heat stress responses, and enhancing the thermal emergency response of vulnerable populations. Future research should aim to further explore the spatial optimization strategies for heat exposure in different urban environments, with a view to validating them with practical cases. This would enable urban planners and renewal officers to make more informed decisions, enhance the adaptability and resilience of cities, and promote sustainable urban development.

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