THERMAL COMFORT, VISIBILITY, AND THE SPATIAL LAYOUT IN CLASSICAL GARDENS OF SUZHOU, CHINA

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Abstract. This study investigated the adaptability of the spatial layout of traditional Chinese gardens to the environment and also visibility. Specifically, we analyzed the layout pattern of traditional gardens, differences in space convenience, and relationship between gardening methods. Moreover, computational fluid dynamics (CFD) was used to simulate physical environments and analyze the comfort of garden spaces and their adaptability to the environment. The results suggested that in the arrangement of the space of the traditional Chinese gardens, the planning of spatial relations was highly consistent with the gardening techniques in addition to conventional visual guidance design. Space syntax which was a common analysis method for spatial planning was used to verify that the winding paths and turning points created visual level changes and spatial contrasts from closed path to open path. Thermal comfort analysis indicated that buildings in the garden were divided to create atmosphere and achieve a visual concealment effect. This paper attempts to combine the perspectives of architectural design and spatial planning to investigate the relationship of thermal comfort, visibility, and the spatial layout of traditional Chinese gardens. It has contribution and innovation to the improvement of garden design in terms of research methods and theoretical applications.
Keywords: *computational fluid dynamics (CFD), thermal comfort, space syntax, environment planning, Chinese gardens*

Introduction

Traditional Chinese spatial layouts are influenced by the concept of “oneness of heaven and humanity” from the Fengshui theory. The theory emphasizes a spatial pattern in which human beings conform to nature and coexist with nature. From city locations and street layouts to traditional residence and gardens, Fengshui exerts a certain level of influence. Fengshui is also similar to other concepts that involve adapting to the environment such as modern ecocity, low-impact development, environmental architecture, and passive houses. Today, the concept of Fengshui still influences architectural and interior design and configuration principles in Chinese societies. Traditional Fengshui theory is built on the worldview of oneness of heaven and humanity and emphasizes natural circulation concepts such as harmony between yin and yang. It considers that all things on earth are interdependent and mutually exclusive and grow and multiply endlessly, aiming to achieve harmony with nature. Lang et al. (2010) reported that Fengshui promotes acting according to circumstances and attempting to create a garden landscape taking into account the original terrain in terms of garden space planning and design. Windings are used as main elements, including appearance winding and path winding. Winding changes are in line with natural patterns, and fortune is considered to occur and accumulate along winding paths. By contrast, misfortune occurs and accumulates along straight paths. Therefore, the traffic flow of traditional gardens are all planned using windings as main elements. Zeng and Qin (2005) summarized the relationship between Fengshui, architecture, and people's lives and proposed that Fengshui involves not only a theoretical discourse but also a practice. Therefore, researchers should not discuss merely the thoughts and models of Fengshui in text. More attention should be paid to the effects and products of Fengshui on the actual context.

Traditional Chinese gardens coexist with nature and are influenced by traditional gardening techniques. Their design concept emphasizes an artistic conception. Different architecture styles could have similar attributes, but they lack systematic standards or guidelines such as Yingzao Fashi published in the Song dynasty and Qing Structural Regulations in the early 20th century. Garden planning methods have not been organized and classified until modern times. Peng (1988) gathered approximately 17 design techniques and characteristics for traditional garden planning. His research is the major systematic work having been conducted in Chinese garden space research. Among the techniques he proposed, contrast (small and big, compressed or expanded) and visual concealment (concealing or revealing) which are the main methods used for creating artistic conceptions in traditional Chinese gardens. In addition to creating moods, previous generations have used the differences in the natural environment and climate to design buildings that suit local climatic conditions through the planning of building routes, selection of building materials, and spatial design, which is the wisdom of responding to climate change (Wang et al., 2016).

Ancient architecture has been an emerging area of research in spatial planning and design as it has adapted to the climate and design concepts (Wang et al., 2016). Michon et al. (1983) and Dilia et al. (2011) point out that traditional Indonesian architecture adapted to the humid tropical climate and created a comfortable living environment through the extensive use of planting in the landscape, the structure and exterior of buildings, and the spatial configuration of buildings to suit the local wind direction. Gómez-Baggethun et al. (2012) examine the adaptability of traditional Spanish settlements to extreme environments. The main focus is on the interaction and resilience of the community, which reflects in the design of the community's architecture and daily life through the experience and knowledge of environmental adaptation passed down from generation to generation. Baran et al. (2011) used field surveys and measurements of the physical environment of traditional buildings in Turkey to analyze the effectiveness of traditional buildings in adapting to the climate regarding thermal comfort and ecological design strategies. Hidayat (2011) points out that the application of traditional architectural design elements in modern architecture is mainly limited to decoration and sculpture, with the primary consideration being to increase the aesthetics of the building rather than utilizing traditional eco-wise design concepts to solve climate problems, mainly because the designers do not understand the environmental context and value of traditional architectural design elements and concepts. Beccali et al. (2018) analyze the natural ventilation benefits and thermal comfort of African terraced buildings as a case study of design elements and case studies and make recommendations that apply to contemporary architectural design. Michael et al. (2017) analyzed the benefits of natural ventilation for cooling in terrestrial buildings in a Mediterranean climate. The results show that cross-ventilation has an excellent cooling effect during summer nights. Chandel et al. (2016) analyzed the building massing, spatial planning, openings, roofing, and material elements of a Himalayan terroir

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building as a case study. The impact on thermal comfort, energy saving, and passive solar heating is used as a reference for modern architecture in terms of thermal comfort.

Nguyena et al. (2011) used computational fluid dynamics (CFD) and Ecotect to model the physical environment of a traditional Vietnamese house and calculated the wind and light environments to verify the impact of architectural design practices on the microclimate of the region. Oikonomou and Bougiatiotib (2011) analyzed the relationship between the traditional Greek built environment and bioclimatic conditions. The built environment comprises form, envelope, materials, and construction, while the bioclimatic consists of heat and visual comfort. The analysis revealed that traditional buildings improve thermal comfort in summer by increasing the number of openings on the windward side to enhance natural ventilation. In winter, the interior is passively heated by solar radiation. Using the example of traditional Korean gardens, Min and Lee (2019) analyze the correlation between geometric (architectural) and environmental data to demonstrate that ecological wisdom helps to regulate the physical environment and can be applied to the sustainable design of buildings. Traditional architecture reflects the wisdom of the ancients in seeking out the natural environment to mitigate the environmental problems caused by climate change. In addition to its effectiveness in adapting to local climatic conditions, the contribution of ancient architecture to thermal comfort in spatial design is of even greater research value in today's urban environment, which is increasingly affected by climate change.

As mentioned earlier, the former approach to environmental planning and design has become an emerging area of research in spatial planning and design. Traditional Chinese garden landscape design focuses on both the psychological environment (mood) and the physical environment (microclimate). In terms of mood, traditional gardening techniques shape the interest in space through different visual perspectives, such as visual contrasts or ambiguity, including the opening and compression of space and changes in visibility. For microclimate, large areas of water, planting, and fencing are used to adapt to the microclimate.

Our research target is the Humble Administrator's Garden located in Suzhou in Jiangsu Province in China (*Fig. 1*). The garden is representative of gardens in areas south of Yangtze River and was first built in 1509. It is one of the four most famous gardens in China and one of the largest gardens among the Classical Gardens of Suzhou. The current appearance of the garden was mostly formed in the early 20th century. It is listed as a world heritage site since 1997. The layout of the Humble Administrator's Garden mainly consists of water accounting for approximately 60% of the total garden area. Additionally, water surrounds the garden, creates spatial division, and influences the overall landscape considerably.

The main objective of this study is to investigate the spatial layout of traditional gardens in terms of their ability to adapt to the environment. The spatial layout is analyzed in terms of visibility, which includes 'visual accessibility' and 'horizons.' In this study, visual accessibility refers to the ease with which a user can perceive or see a spatial location. In contrast, horizons refer to the extent to which a user can see from that location. In spatial planning, people's behavioral activities are guided by vision. Their changing horizons shape their perceptions or experiences of environmental spaces, so visibility analysis can help planners create suitable spatial environments (Bada and Farhi, 2009). We defined visibility as the extent to which the spatial distance between a visual barrier and a visual point is visible. A higher visibility indicates that more space and a longer distance can be observed from the visual point. Conversely, a

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lower visibility indicates that less space and a shorter distance can be observed from the visual point. Visibility can be calculated through a visibility graph analysis (VGA), Convex isovists, and Overlapping point isovists (OPI). This study used Space Syntax to analyze the spatial layout and visualization of the Humble Administrator's Garden. Space Syntax uses visibility graph analysis (VGA) and axial analysis to shape spatial configurations (split configuring) through graphs to analyze the relationship between two spaces and to consider the relationship between all spaces in the system simultaneously, which is a standard mode of analysis for the study of architectural structures, urban areas, human behavior, and social activities (Hiller and Vaughan, 2007).

This study analyses the spatial layout of traditional Chinese gardens in terms of their ability to adapt to the environment through thermal comfort. Thermal comfort refers to the psychological state in which individuals feel satisfied with the environment they are in at the time (Taleghani et al., 2015), in which comfort is a subjective perception of individuals derived from their past experiences, expectations, and reactions to their environmental experiences (Peng et al., 2019). In an urban environment, outdoor open spaces are often seen as an extension of living space (Lau and Choi, 2021), and people are often exposed to the weather during their activities in outdoor spaces, so a comfortable thermal environment is vital for space use satisfaction. People's thermal evaluation of the environment also affects their frequency of use, length of stay, and willingness to revisit the place, and comfortable outdoor spaces enhance urban livability and sustainability (Lau and Choi, 2021), making the comfort of outdoor spaces an essential influence on the design of urban spaces and buildings (Lam et al., 2020). The thermal comfort of the human body is modified by the thermal environment of indoor and outdoor spaces, climate factors, and psychological perceptions, including temperature, humidity, wind, and solar radiation (Lau et al., 2022). Outdoor open space components include roads, buildings, planting, water, and pavement materials. Buildings and facilities affect the amount of shade, while the spatial design of buildings and urban waters (e.g., rivers, lakes, ponds, etc.) affect the driving force of urban wind fields (Lai et al., 2019; Chen et al., 2021). In addition, greenery has excellent potential to facilitate climate change adaptation and mitigation (Peng et al., 2019), and plants can act as solar barriers to prevent overheating of building surfaces and reduce heat absorption in indoor spaces in summer. In outdoor space design applications, adding parks, street trees, or green facades can improve the thermal comfort of pedestrians (Lai et al., 2019; Chen et al., 2021).

As mentioned above, this paper analyses the thermal comfort of traditional Chinese garden design to understand its relationship with climate adaptation. The spatial layout of the building is also an important indicator of thermal comfort, so the spatial layout of the building is assessed through Space Syntax to analyze the degree of spatial visibility of the Humble Administrator's Garden. The higher the degree of visibility, the more space can be seen from the viewpoint and the longer the viewable distance, indicating that the space is less shaded and more spacious, which is conducive to the formation of natural ventilation and improved thermal comfort. Visibility is, therefore, an essential parameter in assessing thermal comfort. This paper also analyses the variation of landscape configuration and physical environment through computational fluid dynamics CFD simulation data, comparing the difference between the landscape space and the external space environment. The study also explores the reasons for the possible influence of gardening elements on the environment. Finally, it presents an influence

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analysis of the garden space's layout on thermal comfort and visibility. The specific research goals are listed as follows:

1. Investigate the effect of the spatial layout of traditional gardens on their comfort and adaptability to the environment.
2. Discuss the effect of the spatial layout of traditional gardens on spatial contrast, concealment construction, and visibility of the gardens.
3. Analyze the correlation between the comfort and visibility of gardens.

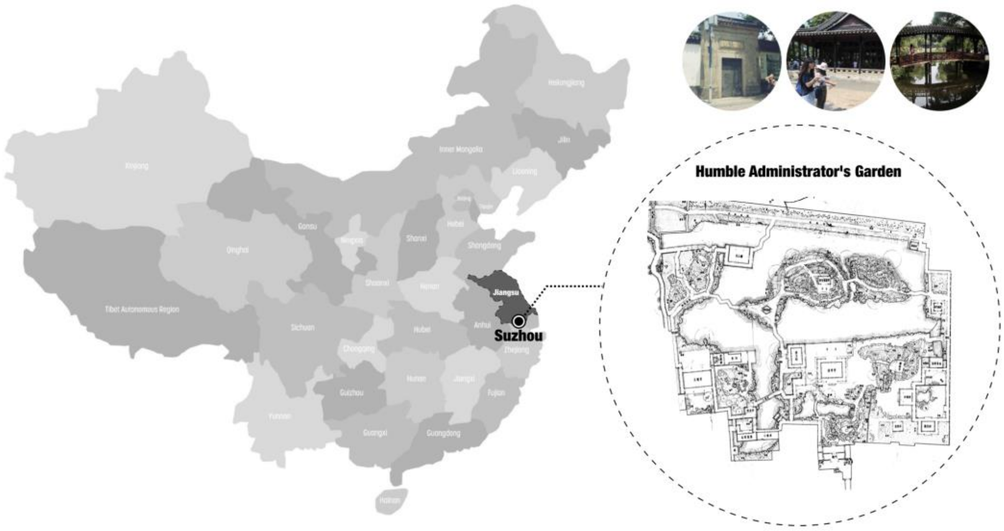

Figure 1. *Location of the Humble Administrator's Garden in Suzhou*

Materials and methods

We analyzed and compared the effects of different spatial layouts used in garden planning on the comfort and visibility of gardens. Our research methods included the calculation of space syntax, CFD, and thermal comfort. The three steps are presented thereafter.

Space syntax

The concept of space syntax was proposed by British scholar Bill Hillier and Julienne Hanson in 1984. Space syntax facilitates the understanding of spatial patterns and their organizational structure and uses formulas for quantitative analysis. Space syntax is a quantitative analysis method that integrates humanistic theories and graphical analysis. In this study, a space with scatter layouts was transformed into a justified graph, and the obtained graph consists of a connecting line segments between nodes and space. Additionally, we quantified the number of nodes and connected segments, calculated their parameters, and analyzed the structural characteristics of globality and locality. The main parameters used in this study were global integration (Rn), local integration (Rr), and visibility graph analysis (VGA). These parameters are described as follows:

Rn (*Eq. 1*) is a comprehensive global indicator that can measure the relative convenience of globality between one element and the others. It first calculates Relative Asymmetry (RAj, *Eq. 2*), the node's centrality in the overall network. Then calculate Real Relative Asymmetry (RRAj, *Eq. 3*) by dividing RAj by the symmetry coefficient

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Dk. The inverse of RRAj is Rn (*Eq. 1*). A larger Rn value indicates a more convenient location in the space network. Rr is a value expressing local convenience and can measure the relative convenience of locality between one element and the others (the range is set by the researcher). A larger value indicates a more convenient location in the local space network.

$$Rn = \frac{1}{RRA_j} \quad \text{(Eq.1)}$$

$$RA_j = \frac{2(MD_j - 1)}{n-2} \quad \text{(Eq.2)}$$

$$RRA_j = \frac{RA_j}{D_k} \quad \text{(Eq.3)}$$

d_{ij}: the shortest path from i point to j point; *n*: the total number of points in the space network; D_k: the symmetry of diamonds (please refer to the table compiled by Hiller and Hanson [1984] for precise values).

Choice (*Eq. 4*) is the measured and assessed value of the shortest path between any two points, and the value indicates the total number of shortest paths through j point and k point. A higher Choice value indicates that main transportation paths are formed more easily.

$$Choice = \sum_j \sum_k \frac{d_{jk}(i)}{d_{jk}} \quad \text{(Eq.4)}$$

d_{jk}: the shortest path from j point to k point; $d_{jk}(i)$: the shortest path through j point and k point.

The concept of visibility graph analysis (VGA) from space syntax theory originated from an analytic model used in landscape spatial analysis. Benedikt (1979) first used this method in architectural space analysis and reported that the visible range could be defined as an isovist field. Hillier and Alaster adopted the concept of visual point analysis and densely covered the examined building with matrix grid points. Each grid represents a visual point in the space and serves to calculate the visual field from each viewpoint. By calculating and sorting the overlapped parts within the field of view, the interactive visual ability from all visual points is displayed, which is referred to as a visual integration. See *Figure 2* for details of the visible area of the viewpoint.

Computational fluid dynamics (CFD)

CFD has been used in the field of construction in recent years, and relevant studies have been conducted from investigations of the urban wind environment to assessments of indoor ventilation effectiveness and verified that numerical simulation (i.e., CFD) results are similar to the actual data obtained from measurements (Takahashi et al., 2004; Hu and Wang, 2005). This confirms that research outcomes from this type of boundary condition settings, grid design, and computational domain has reasonable reliability. Historical data can then be applied to simulate the physical environment at a certain period. This study used CFD to simulate the physical environment of the Humble Administrator’s Garden and observe climatic parameters to calculate its thermal comfort.

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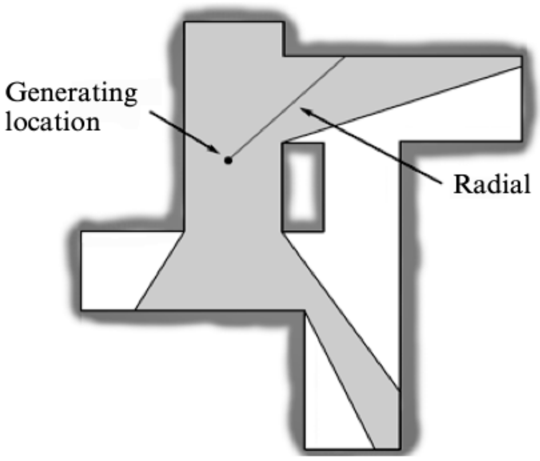

Figure 2. *Visibility area viewpoint description (Turner et al., 2001)*

Climatic condition setting

We referred to the data derived from a climate reconstruction model of Suzhou established using Weather Spark (official website: https://zh.weatherspark.com) for our climatic data. The data are based on a statistical analysis of the climate from 1980 to 2016. Suzhou weather was reconstructed using MERRA-2 (NASA) model. The climatic condition settings by Weather Spark that we referred to are presented in *Table 1*.

Table 1. *Climate parameters of Suzhou*

Season	Temperature	Wind speed	Major wind direction	Relative humidity	Mean radiant temperature (MRT)	Physiological equivalent temperature (PET)
Summer (July)	27.8 °C	4 m/s	South	76%	54.1 °C	32.7 °C
Winter (January)	3.7 °C	4 m/s	North	72%	24.6 °C	−2.7 °C

Scope of Data Statistics 2015~2019

Settings of boundary condition and grids

Grid is a key factor in calculating CFD flow field, and grid quality determines the accuracy of a flow field, defines the accuracy of boundary conditions, and solves control equations through numerical methods. Our research model used unstructured grids to create a finer grid on the inclined planes of numerous traditional buildings. On the model boundary, the inlet boundary was defined as “Velocity inlet”, whereby the inlet flow rate and settings of relevant parameters were set. Wind speed gradient was set to conform to the natural state of the atmosphere. The outlet boundary was defined as “Pressure outlet”, and the backflow direction was set to reduce the difficulty of convergence of the model. The boundary between the Earth’s surface and the building was defined as “Wall”, and the remaining boundaries were defined as “Symmetry”. The physical quantitates inside and outside the boundary were equal, and they were used to simulate the extension of the atmosphere and avoid solving the entire computational domain. The model boundary settings and size are illustrated in *Figure 3*. The blockage ratio of “flow domain” was lower than 5%, which prevented a blockage effect from occurring (Barlow et al., 1999).

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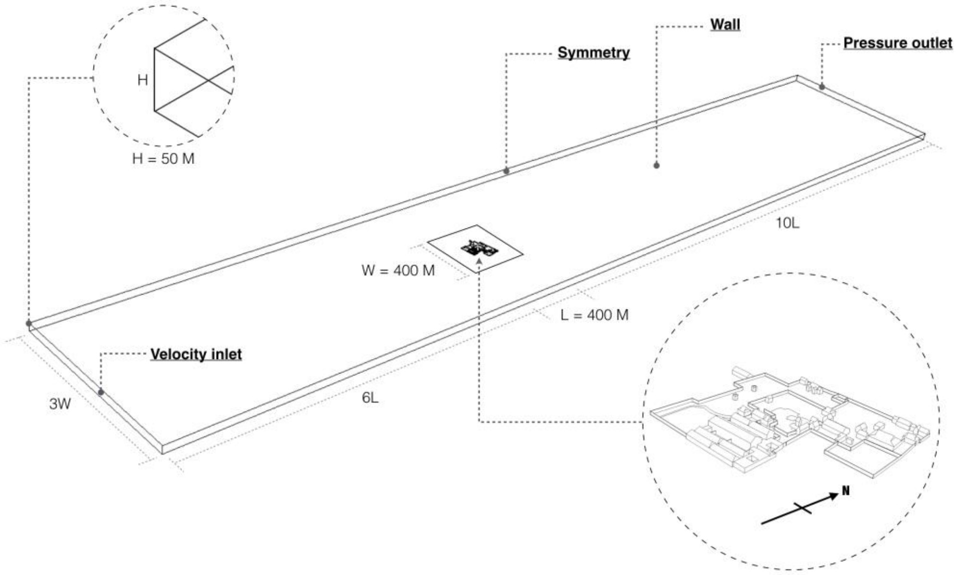

Figure 3. *Boundary conditions*

Wind gradient setting

In the natural state of the atmosphere, the wind speed near the Earth's surface is affected by the friction effect created by different degrees of surface roughness (such as terrain fluctuations and building distribution). Wind speed closer to the Earth's surface is slower in the natural state of the atmosphere. The vertical wind direction distribution of the wind profile is as follows:

$$\frac{U(z)}{U_n} = \left(\frac{z}{\delta}\right)^{\alpha} \quad \text{(Eq.5)}$$

where Z is the height, Z_{ref} is the reference height, $U_{(Z)}$ is the wind speed of the height Z, U_{Zref} is the average wind speed of the reference height, and the magnitude of α value is determined by surface roughness and atmospheric stability. In this study, the boundary of the velocity inlet is substituted for the wind profile (*Eq. 5*) in this model. The wind speed of reference height (Z_{ref} is 10 m in our study) outside the boundary layer of each model was set to 1.5 m/s, 1.7 m/s, 2.2 m/s, and 2.8 m/s according to the settings presented in *Table 1*. This study followed the recommendations of the British Standards Institution in 1991, which proposed the suitable α values for four different terrains, namely centers of big cities, suburbs and small towns, open plains, and flat coastal or lake areas (0.33, 0.25, 0.20, and 0.17, respectively). In this study, we set α to 0.25, calculated the wind speed $U_{(Z)}$ of each height (*Fig. 4*), and substituted the resulted values into the setting of inlet boundary (velocity inlet) in the model.

Thermal comfort

Numerous types of indicators can be used to assess thermal comfort. Honjo (2009) verified that physiological equivalent temperature (PET) is suitable to assess urban thermal environments. Therefore, we used physiological equivalent temperature (PET) as main indicator and assessed the thermal comfort of open spaces. A higher level of spatial thermal comfort increases people's willingness to stay longer. The physiological

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equivalent temperature (PET) is affected by temperature, humidity, wind speed, radiation, clothing layers, and physical activity of the human body at measurement. The physiological equivalent temperature (PET) can be defined as the thermal equilibrium state of the human body in a typical urban environment, radiation temperature, somatosensory temperature, and complex environment. This state is transformed and expressed in air temperature. The thermal equilibrium equation proposed by Höppe (1999) is as follows:

$$M + W + C + R + E_D + E_{RE} + E_{SW} + S = 0 \quad \text{(Eq.6)}$$

Equation 6 is an basic equilibrium equation for the human body heat, where M is the metabolic rate (W/m^2), W is the physical work output (W/m^2), C is the convective heat flow (W/m^2), R is the radiation temperature (W/m^2), E_D is the perspiration rate, E_{RE} is the contrast between breathing heat and heat flow loss rate (W/m^2), E_{SW} is the heat loss due to evaporation of sweat (W/m^2), and S is the heat flow storage for regulating body temperature (W/m^2). The Munich Energy-Balance Model for Individuals (MEMI) was the foundation of the physiological equivalent temperature (PET) calculation as follows:

$$F_{cs} = v_b \times \rho_b \times c_b \times (T_c - T_{sk}) \quad \text{(Eq.7)}$$

where F_{cs} (*Eq. 7*) is the heat flux conservation equation of the core temperature to the body surface temperature, v_b is the blood flow from the core of the body to the surface of the body, ρ_b is the blood density, c_b is the specific heat, T_c is the average core temperature, and T_{sk} is the average body surface temperature.

$$F_{sc} = (1 / I_{cl}) \times (T_{sk} - T_{cl}) \quad \text{(Eq.8)}$$

Fsc (*Eq. 8*) is the heat flux conservation equation from the body surface temperature to the surface of garments, I_{cl} is the heat resistance of garments, T_c is the average core temperature, and T_{sk} is the average body surface temperature.

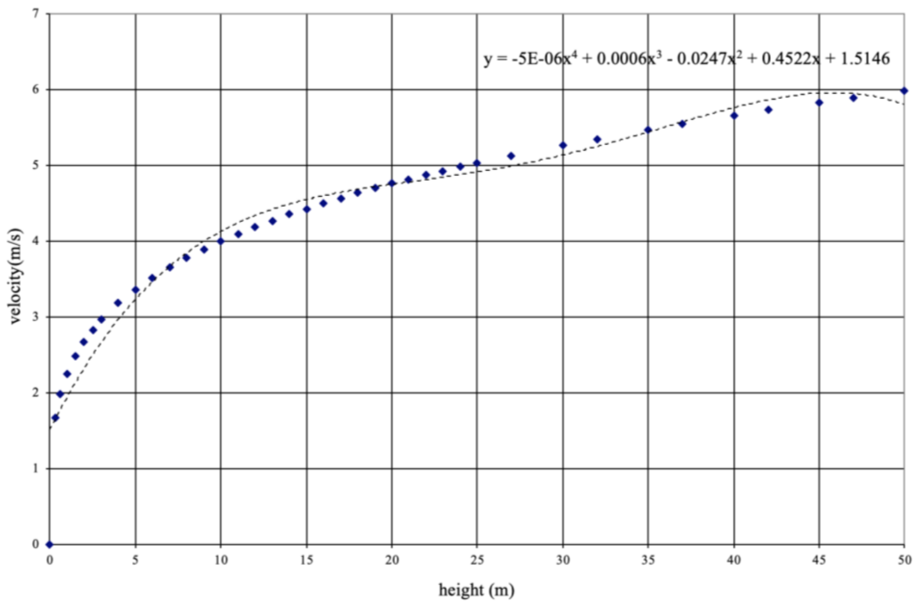

Figure 4. *Wind gradient*

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The physiological equivalent temperature (PET) was calculated according to the following steps: (1) enter climatic parameters and use the MEMI model to calculate the heat state of individuals; (2) enter the computed values of average core temperature and average body surface temperature into the MEMI model; (3) solve the equation and obtain the value of air temperature Ta. At this time, Ta, the air temperature value, is the physiological equivalent temperature (PET) value. The thermal perceptions and degrees of physiological stress of corresponding the physiological equivalent temperature (PET) indices are presented in *Figure 5*.

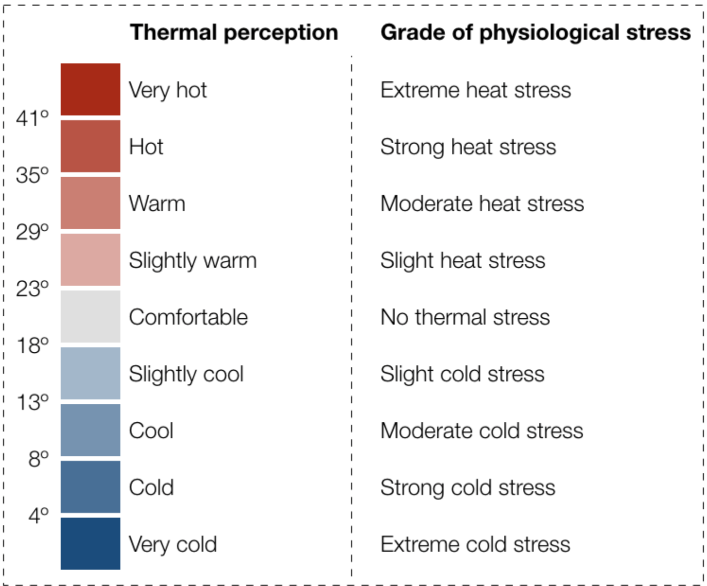

Figure 5. *Corresponding grades of physiological stress according to the physiological equivalent temperature (PET) indices*

Results and discussion

Spatial structure analysis of the Humble Administrator's Garden

This study divided the Humble Administrator's Garden into 7 areas (*Fig. 6*). Area A was the entrance, areas B, C, and D were the main building areas, areas E and F were the building areas adjacent to the water, and area G was the north-side periphery. In the spatial analysis, we first discussed the traffic flow planning of the garden through local integrated value (R3), Choice value, and visibility graph analysis (VGA) value obtained from space syntax to obtain the convenience value, optimal efficiency path, and openness of the field, respectively. A higher R3 value indicated higher road accessibility and space openness. A lower R3 value indicated lower road accessibility and space openness. Choice value was used to plan the optimal garden route and analyze changes in contrast among the different spaces during visitors' visits. A higher visibility graph analysis (VGA) value indicated a higher visibility, and a lower visibility graph analysis (VGA) value indicated a lower visibility. By adopting space syntax, we compared and analyzed the convenience level, major routes, and visibility using R3 value, Choice, and visibility graph analysis (VGA), respectively.

According to the results of Choice value analysis illustrated in *Figure 7,* the main path of the Humble Administrator's Garden (red line) was divided into two main routes after

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entering the garden. The lines pass through each area of the garden, and they are the most efficient paths. The lines cover the blocks of the entire garden with the exception of road to the northwest, which exhibits a relatively low Choice value. However, all five blocks of the garden from block A to block E are accessible by the main routes. Results of the analysis of R3 depicted in *Figure 8* suggested that four parts of the Humble Administrator's Garden have a relatively high convenience value (red circles). They are distributed in different locations of the garden including the cluster of buildings at the northwest, the outer east, and the south, and the area connecting with the island in the middle. This result indicated that the four places had great accessibility and high spatial openness. Moreover, the distribution of the four places was even. Combining the results obtained from R3 and Choice value analyses, three of the roads with higher convenience values and more open space appeared to be located on the main route. Through spatial layout and traffic flow planning, all areas were connected, and the effects of open space and hidden twists during the visit in the garden were observed. Moreover, this design enabled an even distribution of layout within each area and successfully connected the routes of each area in the garden. A visibility graph analysis (VGA) of the Humble Administrator's Garden as presented in *Figure 9* indicated that the lowest visibility was mainly found at the entrance of area A. The view was blocked by numerous plants and walls. Therefore, visibility decreased. The areas with the second lowest visibility level were the garden boundary and building clusters, and they are mainly located in areas B, D, and G. These areas were influenced by the boundary walls and buildings and had lower visibility. The F area that comprises a water domain had the highest visibility, and the view was not blocked by anything except for the Xuexiangyunwei Pavilion (in the center of F area). The areas with the second highest visibility level were the main spatial clusters surrounding the water domain, including area E and area C. These areas face the broad water domain, and the view is less obstructed.

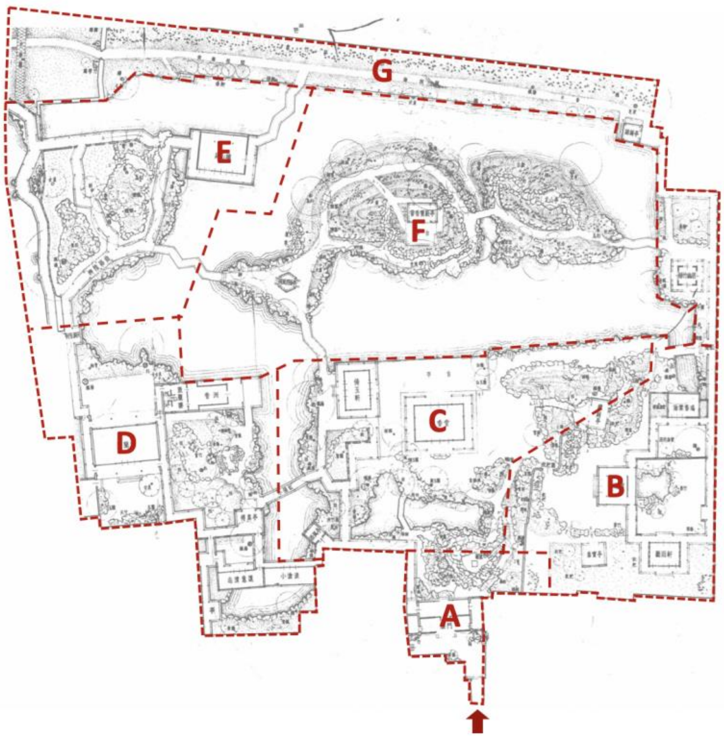

Figure 6. *Areas of the Humble Administrator's Garden*

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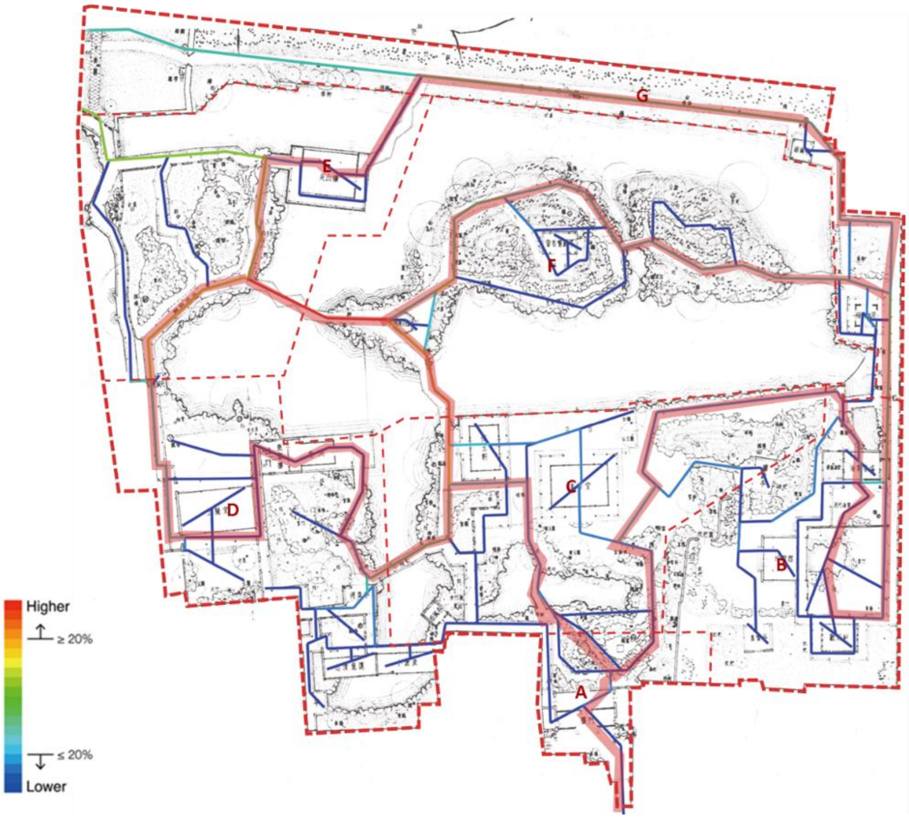

Figure 7. *Choice value analysis of the Humble Administrator's Garden*

Figure 8. *Locally integrated value (R3) analysis of the Humble Administrator's Garden*

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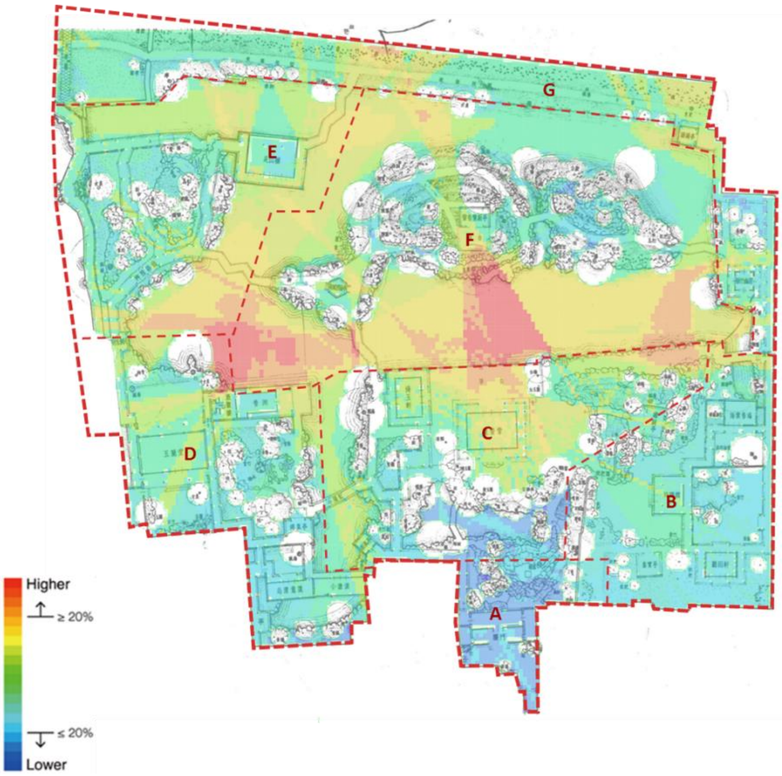

Figure 9. *Visibility graph analysis (VGA) of the Humble Administrator's Garden*

We analyzed the spatial sequence of the main routes in *Figure 7* and overlapped R3 (*Fig. 8*) and visibility graph analysis (VGA) (*Fig. 9*) to determine the contrastive changes in spatial transformation of the main routes (*Fig. 10*). In terms of convenience, areas with greater accessibility corresponded to major stop points for visitors. Starting at the garden entrance, in terms of changes in convenience, 6 major changes and transitions were observed. Mostly, increases and decreases in convenience were noted before and after passing through the clusters of buildings. In terms of visibility, starting at the lowest entrance, four major changes in visibility occurred between the main garden visiting routes. The first change occurred when visitors passed through the plants and wall covering the entrance. At this location, part of the open water domains could be observed on the left, and visibility increased, but after entering the clusters of buildings, visibility decreased. The second change in visibility took place when visibility increased again after visitors passed through the trees and crossed the bridge. Visibility decreased again after they entered the tree area on the island. The third change took place when visitors arrived at the major stop point on the island, and visibility was at its highest there because the visitors were facing the water domain. Visibility decreased again following visitor's entry into the tree area on the island. The fourth change occurred when visitors passed through plants at the garden boundary and walked along the shore. At this point, their visibility increased and remained consistent until they returned to the entrance, where the visibility again decreased. A comparison of the line chart of convenience and visibility distributions indicated that the correlation between the two was not high, and their lines actually took an opposite direction. In terms of changes in convenience, spatial clusters with more buildings and auxiliary spaces had higher levels of convenience. In terms of changes in visibility, spatial clusters had lower visibility because of various buildings and

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surrounding plants. The highest visibility was observed in the middle of the water domain, which is hard to reach.

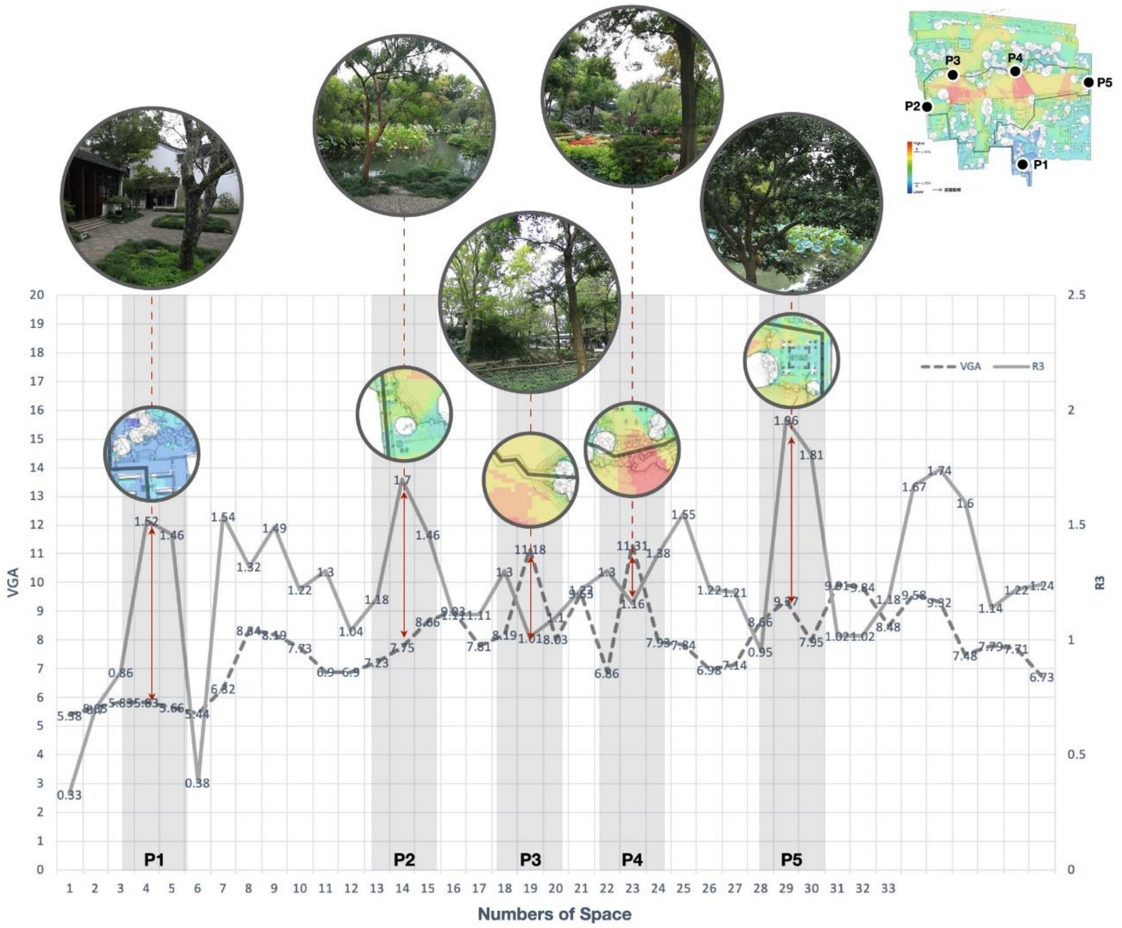

Figure10. *Distribution of visibility graph analysis (VGA) and locally integrated values (R3) of the traffic flow of the Humble Administrator's Garden in Suzhou. Note: R3 and visibility graph analysis (VGA) is dimensionless number*

Thermal comfort analysis

Table 2 indicates that the overall physiological equivalent temperature (PET) in the summer dailytime, the anges between 37.9 °C and 41.6 °C in the Humble Administrator's Garden, and the mean is 40.1 °C. Thermal perception distribution ranges from hot to very hot (*Fig. 11*), which is relatively uncomfortable compared with the physiological equivalent temperature (PET) of the external climate environment (35.3 °C; warm). Analysis of individual climatic parameters revealed that the temperature inside the Humble Administrator's Garden (average 27.71 °C to 27.73 °C) was lower than the outside temperature (27.8 °C). However, the wind speed inside the garden (a mean of 0.83 to 0.95 m/s) at a height of 1.5 m was substantially lower than the wind speed outside the garden (2.49 m/s) at a height of 1.5 m. Observations of the wind speed plane can explain this difference in wind speed. Specifically, a large number of walls were constructed and densely planted trees were planted in the interior of the Humble Administrator's Garden. Therefore, the wind was unable to enter the garden.

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The physiological equivalent temperature (PET) at summer night is calculated as a lower overall thermal comfort due to the higher temperatures. The temperature distribution is between 35 and 38.6 °C, with all thermal sensations being hot, and the ranking of thermal comfort in each area is the same as during the day.

During the winter in the night, the inside of the Humble Administrator's Garden had an overall physiological equivalent temperature (PET) of between 1 °C and 13 °C, with an average of 6.6 °C. The physiological equivalent temperature (PET) ranged 7.3 °C–12.0 °C when the wind direction was east and averaged 10.2 °C. Said results indicated that thermal perception was from very cold to cool, and the temperature was comfortable overall compared with the physiological equivalent temperature (PET) (−0.4 °C; very cold) outside the garden (*Fig. 12*). An analysis of individual climatic parameters revealed that the temperature inside the Humble Administrator's Garden was relatively low (a mean of 3.61 °C to 3.65 °C) compared with the temperature outside the garden (3.7 °C). This weather difference was similar to that during summer. However, the wind speed inside the garden (a mean of 0.81 to 0.92 m/s) at a height of 1.5 m was substantially lower than the wind speed (2.49 m/s) outside the garden at the same height. The reason for such weather difference was the same as that in summer. That is, a large number of walls and densely planted trees were used in the interior design of the Humble Administrator's Garden. Therefore, the wind was unable to enter the Humble Administrator's Garden. The physiological equivalent temperature (PET) at winter night in Humble Administrator's Garden is lower in overall thermal comfort due to the lower temperature. The temperature distribution ranged from 0.6 to 1.8 °C, with the thermal sensation being very cold. The ranking of thermal comfort in each zone is only slightly different between zone C and zone F. In principle, the ranking is the same as during the day.

Table 2. *The physiological equivalent temperature (PET) of the Humble Administrator's Garden*

Code	Division	Summer PET (°C) / comfort sequence		Winter PET (°C) / comfort sequence	
		Daytime	Night	Daytime	Night
A	Entrance	41.3 (6)	38.3 (6)	12.0 (1)	1.8 (1)
B	Periphery of Linglong Complex	41.6 (7)	38.6 (7)	9.4 (6)	0.7 (6)
C	Periphery of Yixiang Hall	39.3 (2)	36.1 (2)	11.6 (2)	1.5 (3)
D	Periphery of Yulan Hall	40.9 (5)	37.8 (5)	10.0 (5)	1.2 (5)
E	Periphery of Jianshan House	39.8 (3)	36.9 (3)	7.3 (7)	0.6 (7)
F	Periphery of the Xuexiangyunwei Pavilion	37.9 (1)	35.0 (1)	10.9 (3)	1.6 (2)
G	Outside the north-side boundary	40.1 (4)	37.2 (4)	10.5 (4)	1.3 (4)
	Mean	40.1	37.1	10.2	1.3

In terms of spatial comfort, areas B, A, D, and G mainly located in peripheral areas and thus had higher physiological equivalent temperature (PET) and lower comfort levels. These areas were closer to the garden boundaries and resisted more to the circulation of wind. Additionally, they were further from the main water body. Therefore, their temperature adjusting function could not be used. The roads of areas E, C, and F were twisted and surrounded by more plants. Moreover, they were bordered with a water body, which facilitated temperature reduction. They had higher comfort levels in the summer. The overall architectural space was relatively warm and more heated in the summer, but it was more comfortable and warmer in the winter. The main building clusters (C and D) remained comfortable and did not change sequence according to different wind directions

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or seasons. These areas are adjacent to large water areas, which suggested that water helps stabilize the thermal comfort of the environment.

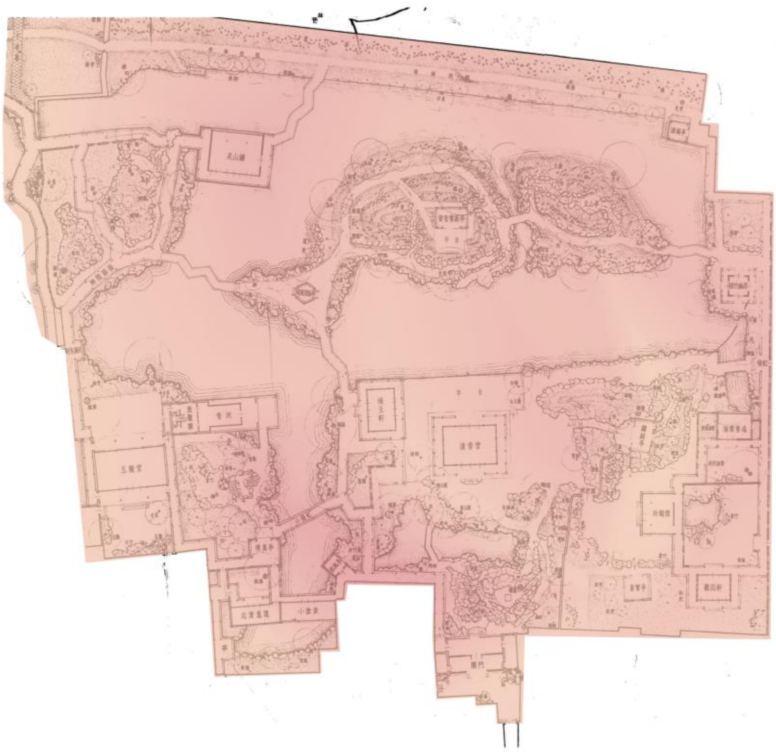

Figure 11. *The physiological equivalent temperature (PET) color temperature of the Humble Administrator's Garden of Suzhou in summer (south wind)*

Figure 12. *The physiological equivalent temperature (PET) color temperature of the Humble Administrator's Garden of Suzhou in winter (north wind)*

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Conclusion

By focusing on the Humble Administrator's Garden, this study analyzed the spatial structure and compared landscaping techniques using space syntax. We also analyzed the garden environment comfort through CFD. The results suggested that in the arrangement of the space of the Humble Administrator's Garden, the planning of spatial relations was highly consistent with the gardening techniques in addition to conventional visual guidance design. In terms of spatial comfort, major building clusters (C and D) were relatively comfortable in winter and summer.

Spatial structure analysis suggested that the planning and design of the Humble Administrator's Garden used suitable gardening techniques. Winding paths and turning points created visual level changes and spatial contrasts from closed path to open path. This phenomenon was most apparent when visitors crossed the main entrance to the garden. Additionally, the analysis suggested that the stop points in the garden adopted suitable gardening techniques in addition to conventional visual guidance design.

Thermal comfort analysis indicated that buildings in the garden were divided to create different feelings and achieve a visual concealment effect. The interior walls, in addition to the exterior ones, were designed as enclosure walls with densely planted trees to achieve a visual concealment effect. When such design is applied to a smaller garden, it can prevent the wind from entering the garden. However, because the Humble Administrator's Garden is relatively big and has a large water domain area, the wind could still enter the garden. Moreover, with the temperature regulation effect of water body, the main building clusters (C and D) had more stable thermal comfort changes and relatively higher comfort in winter and summer.

In terms of spatial distribution, emphasis was placed on taking advantage of existing resources when building gardens in areas south to Yangtze River. That is, gardens were built based on the existing natural terrain at the time. Consequently, the gardens' overall layout does not entirely satisfy the ideal layout from traditional Fengshui theory. For example, the east and west sides of the garden should have a higher terrain. Nevertheless, utilization of existing resources and retaining natural terrain enabled the Humble Administrator's Garden to better adapt to the local natural environment. The main building clusters (C and D) are surrounded by water, and the south side of the building clusters in summer is not blocked, enabling the south wind to enter the building clusters. This, in turn, decreases thermal comfort and makes the level of physiological stress very hot in summer. In winter, although open water domains are present in the north, small islands on the north side of the waters are densely planted with trees. This effectively shields the north wind from entering the building directly, making the garden relatively warm and comfortable.

We took the research methods of a previous study as reference and conducted a numerical analysis of the physical environment of traditional buildings. Although complete reconstruction of the real physical environment of the garden is difficult, the level of comfort can still be revealed by making comparisons. This helps determine whether a garden planning design is conducive to improving the comfort level in an environment. Overall, in addition to previous qualitative studies conducted on different artistic conceptions, the spatial analysis method can be used to conduct quantitative research on spatial characteristics. This research method enables researches to clearly represent the quantitative changes occurring in the spatial perception of the traveling routes for garden visits. Comparisons between the spaces of different gardens can be made. However, space syntax has its limitation in terms of analysis. For example, the

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subjective factors used for spatial division by different analysts may affect analytical results. Therefore, we recommend that the principles of space division should be formulated and fully discussed in the space division stage. This will help avoid divergence in the research outcomes generated by differences in the spatial perceptions of analysts. In a visibility graph analysis (VGA), the calculation formula considers only the influence of the plane. However, humans have a stereoscopic feeling about a space. We recommend future studies to incorporate visual analytical tools with stereoscopic analysis features to make comparisons. This paper attempts to combine the perspectives of architectural design and spatial planning to investigate the relationship of thermal comfort, visibility, and the spatial layout of traditional Chinese gardens (Humble Administrator's Garden). It has contribution and innovation to the improvement of garden design in terms of research methods and theoretical applications.

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