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Unveiling the dynamics of "scenes changing as steps move" in a Chinese classical garden: a case study of Jingxinzhai Garden

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Abstract

Chinese classical gardens are a significant cultural heritage in the history of world gardening, with their central architectural principle of "scenes changing as steps move" (步移景异) embodying traditional Chinese aesthetic ideals. This study employed the variation of visual complexity during a tour as a representation of this principle, using Jingxinzhai (静心斋) Garden as a case study. The visual environmental characteristics were quantified using the Fraclab box-counting, Canny edge detection, and DeepLab V3 + model, and the spatial distribution of fractal dimension and visual index of landscape elements were analyzed. Through partial correlation analysis, hierarchical regression analysis, and one-way ANOVA, the relevant factors (BVI, RVI, GVI, WVI) and influencing factors (BVI, RVI, GVI) and the differences among landscape element combinations of visual complexity were identified. Furthermore, the distribution patterns and causes of visual complexity in Chinese classical gardens were then discussed. This study proposes an effective method for quantifying the visual environmental characteristics of Chinese classical gardens and provides an explanation of the concept of "scenes changing as steps move" from the perspective of visual environment. It offers important references for a deeper understanding of Chinese classical garden design and planning.

Keywords Chinese classical gardens, Jingxinzhai Garden, Fractal dimension, Landscape elements, Scenes changing as steps move

Introduction

Chinese classical gardens are not only an important part of traditional Chinese culture, but also a significant component of world cultural heritage. They embody various aspects of ancient Chinese culture, philosophy, art, and technology, with unique artistic and historical value in their design concepts, architectural styles, and garden layouts. In Western gardens, symmetrical and regular spatial design is typically employed, emphasizing static beauty [1], while Chinese classical gardens often use an asymmetrical, curved, and free-form spatial design [2], emphasizing the concept of "scenes changing as steps move" (步移景异). As visitors move through the garden, the landscapes transform along with their footsteps, creating a dynamic and continuous viewing experience. Thus, despite the modest size of certain Chinese classical gardens, the abundant and varied visual environment prevent visitors from experiencing boredom within these confined areas [3].

The term "scenes changing as steps move" suggests that "steps move" refers to movement and incorporates aspects of chronological alteration, while "scenes changing" refers to the visual manifestations that result from the passage of time. In simple terms, whenever the visitor's perspective changes, the original state of all landscape elements and their relationships with each other will also change

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accordingly [4]. The essence of spatial perception is the process of obtaining information through movement in space, and the visual environmental characteristics of space are an important factor affecting spatial perception. Therefore, using the variation of visual complexity as a representation of "scenes changing as steps move", quantifying the visual environmental characteristics in Chinese classical gardens, and analyzing the landscape elements that affect changes in visual complexity during the "steps move" process can help us understand the distribution patterns and causes of "scenes changing as steps move" in Chinese classical gardens.

In addition to the traditional methods of observation and evaluation [5, 6], researchers in relevant disciplines have progressively adopted computer technology to aid in quantifying the visual environmental characteristics. Among them, fractal dimension, as a statistical parameter in fractal geometry theory [7], serves as a measure that describes the complexity or irregularity of a fractal object or pattern, while also providing insights into the extent of space filling and the brokenness of the shape. It is frequently utilised as an indicator to quantify the visual complexity in the built environment [8, 9] and has been applied in studies on architectural design [10–14], urban structures [15–17], street landscapes [18, 19], as well as Chinese classical gardens. For example, Yu Aokun et al. used the box-counting dimension to measure the contours of buildings, rockeries, and pool banks in the garden plan, and explored the influence of the layout characteristics of the tour route on the visual complexity of the Liuyuan [20]. Xu Tong et al. conducted a calculation of the fractal dimension of Chinese classical gardens and waterfront promenade in urban park in order to analyse and contrast the disparities between the two [21]. Ding Mingjing et al. conducted a study on the fractal dimensions of rockeries in gardens based on the combination types divided by viewing facades elements [22]. Besides fractal dimension, the visual index of landscape elements is also regarded as an important indicator for quantifying visual environmental characteristics. It is extensively employed in studies on landscape preferences [23–25], environmental perception [26, 27], environmental quality assessment [28], and other studies related to street view analysis. Researchers commonly use semantic segmentation technology to identify and classify landscape elements such as plants, buildings, rivers, and so on in street view images.

Nevertheless, there remain certain limitations in the current research on the visual environmental characteristics of Chinese classical gardens. Firstly, the majority of current researches continue to use the garden plan as the foundation for their study. Unlike formal gardens, Chinese classical gardens necessitate dynamic perspectives for comprehensive observation. A set of visual objects often possesses multiple viewing facades [29], and visual environmental characteristics change as visitors navigate around the area, leading to the captivating sensation of "one step, one scene, with scenes changing as steps are taken". Therefore, this study analyzes the visual environment of Chinese classical gardens from the perspective of the visual scenes experienced by visitors in the garden. Furthermore, in contrast to the conventional spatial arrangement where buildings are given priority and other elements are considered less important, Chinese classical gardens are characterized by the organic integration of four key landscape elements: buildings, rocks, plants, and water [4]. Therefore, this study examines and analyzes these elements as an integrated system. Lastly, current research on Chinese classical gardens is largely qualitative. Therefore, this study employs fractal dimensions and image semantic segmentation to objectively describe the visual complexity of environment in gardens and efficiently extract the shapes and edges of landscape elements such as buildings, rocks, plants, and water, laying a foundation for future quantitative research on Chinese classical gardens.

This study takes the Jingxinzhai(静心斋) Garden as an example and focuses on the visual complexity and visual index of landscape elements (both individual landscape elements and landscape element combinations) as key visual environmental characteristics of Chinese classical gardens. It utilizes computer vision technology to assist in analyzing the patterns and causes of the phenomenon of "scenes changing as steps move". The primary concerns of the study are as follows:

(1) Effectively and accurately calculate the fractal dimension and visual index of landscape elements.
(2) Analyze the spatial distribution of the fractal dimensions and visual index of landscape elements in the Jingxinzhai Garden.
(3) Investigate the relationship between the visual index of landscape elements and fractal dimension.

Methodology

Study area and data collection

The Jingxinzhai Garden is located within Beihai Park in Beijing. It has a building area of 1912.87 square meters and a total land area of 4700 square meters. Jingxinzhai Garden was built in the 21st year of the Qianlong reign (1756), originally named Jingqingzhai (镜清斋), as the study area of the crown prince. After a large-scale renovation in the 13th year of the Guangxu reign (1887), it formed the current layout. Jingxinzhai Garden is divided into four courtyards: the front yard (FY), the west court (WC), the east court (EC), and the backyard [30]. Each courtyard is cleverly separated by the arrangement of buildings and landscapes, while also being connected by corridors to form a unified entity. FY is a square pool area that is surrounded by the mian gate, the main hall of Jingxinzhai, and the corridors. FY is flanked by two relatively independent courtyards, WC and EC. The backyard is the main scenic area of the garden. According to its landscape characteristics, it is further divided into two parts: backyard-courtyard (BC) and backyard-rockery (BR) (Fig. 1).

In the arrangement of sampling points, this study followed the tour route of the garden, setting a sample point every 2 m, with a total of 311 points. There are a total of 32 points in the FY, 32 points in the WC, 42 points in the EC, 99 points in the BC, and 106 points in the BR (Fig. 2). In order to better simulate the actual perspective of visitors, who typically observe their surroundings in a 360-degree manner, this study set up a camera with a height of 1.5 m and a focal length of 35 mm at the sample point, and recorded images every 60°[27], capturing a total of 6 angles (Fig. 3). A total of 1866 base images were collected. In the following study of fractal dimensions and visual complexity of landscape elements, the average of the six angular images was used as the value of the sample points. The overall framework of the study is shown in Fig. 4.

Fractal dimension calculation

The calculation process of fractal dimension is as follows: First, the image needs to be binarized to convert it into a black and white binary image to identify the edge structure information of landscape elements. Secondly, an edge detection algorithm is used to extract the edge structure information of landscape elements in the image, providing a basic wireframe file for the subsequent fractal dimension calculation. Then, the fractal dimension of the image is calculated using the box-counting dimension, and the results of the fractal dimension calculation will be presented in numerical values, which can be used to analyze the visual complexity of the Jingxinzhai Garden.

Image edge detection based on Canny algorithm

Edge structural information can help us more accurately identify and describe the morphological characteristics of landscape elements, thereby achieving the calculation of fractal dimensions. In current research in the field of built environments, the edge structural information of landscape elements is often based on CAD files. Considering that CAD may not adequately represent the actual scenes composed of multiple landscape elements, this study used edge detection algorithms to extract boundary structural information of landscape elements in garden images [10,

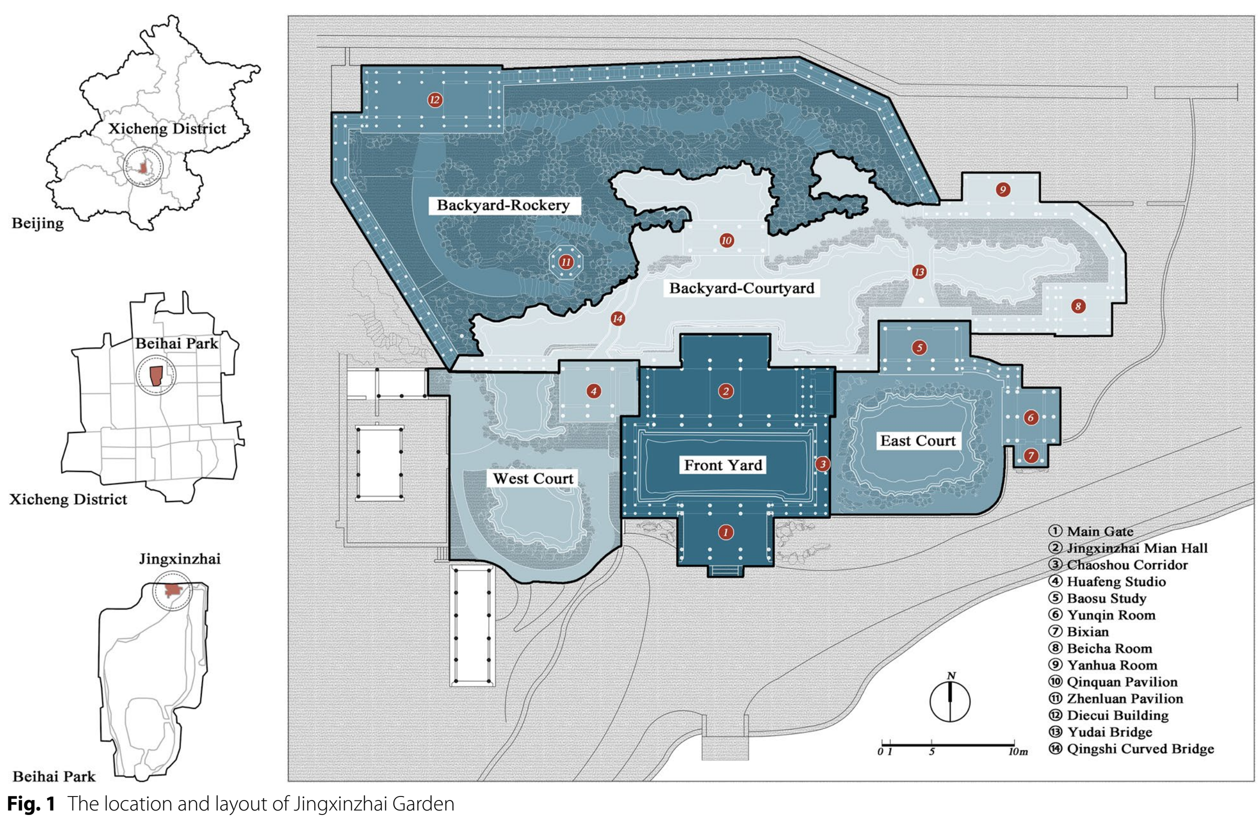


Fig. 1 The location and layout of Jingxinzhai Garden

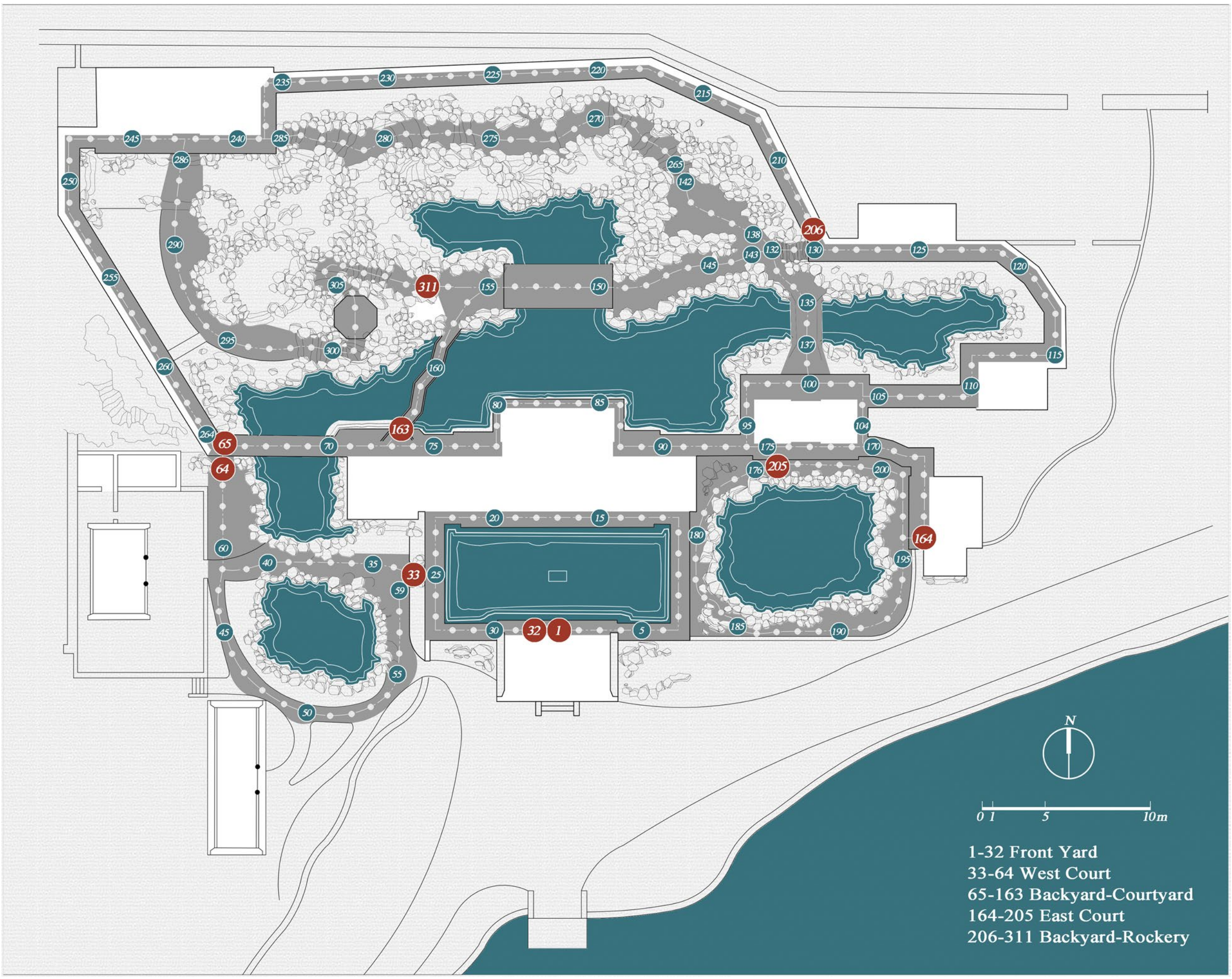


Fig. 2 Distribution of sample points

31]. Edge detection is widely used in computer vision and image processing, and common algorithms include Roberts algorithm, Sobel algorithm, Prewitt algorithm, LOG algorithm, and Canny algorithm [32]. By comparing the output results of various edge detection algorithms, this study found that the Canny algorithm has advantages in terms of noise resistance, computational complexity, and identification accuracy. Consequently, it was employed to execute edge detection on the sample images (Fig. 5). The The algorithm process is as follows (Fig. 6):

Firstly, a Gaussian filter is applied for image denoising. Let the input image be f(x, y), and the image is smoothed using the distribution of a two-dimensional Gaussian function, as shown in the following formula:

$$G(i,j) = \frac{1}{2\pi\delta^2}\exp\left(-\frac{i^2+j^2}{2\delta^2}\right) \quad (1)$$

In the formula, δ represents the standard deviation of the Gaussian function.

Next, calculate the gradient magnitude and direction of the pixels in the sample image:

$$G_x(i,j) = \frac{p(i,j+1) - p(i,j) + p(i+1,j+1) - p(i+1,j)}{2} \quad (2)$$

$$G_y(i,j) = \frac{p(i,j) - p(i+1,j) + p(i,j+1) - p(i+1,j+1)}{2} \quad (3)$$

$$L(i,j) = \sqrt{G_x(i,j)^2 + G_y(i,j)^2} \quad (4)$$

$$\theta(i,j) = \tan^{-1}\frac{G_y(i,j)}{G_x(i,j)} \quad (5)$$

In the formula, $G_x(i,j)$ represents the first-order partial derivative in the horizontal direction, $G_y(i,j)$ represents

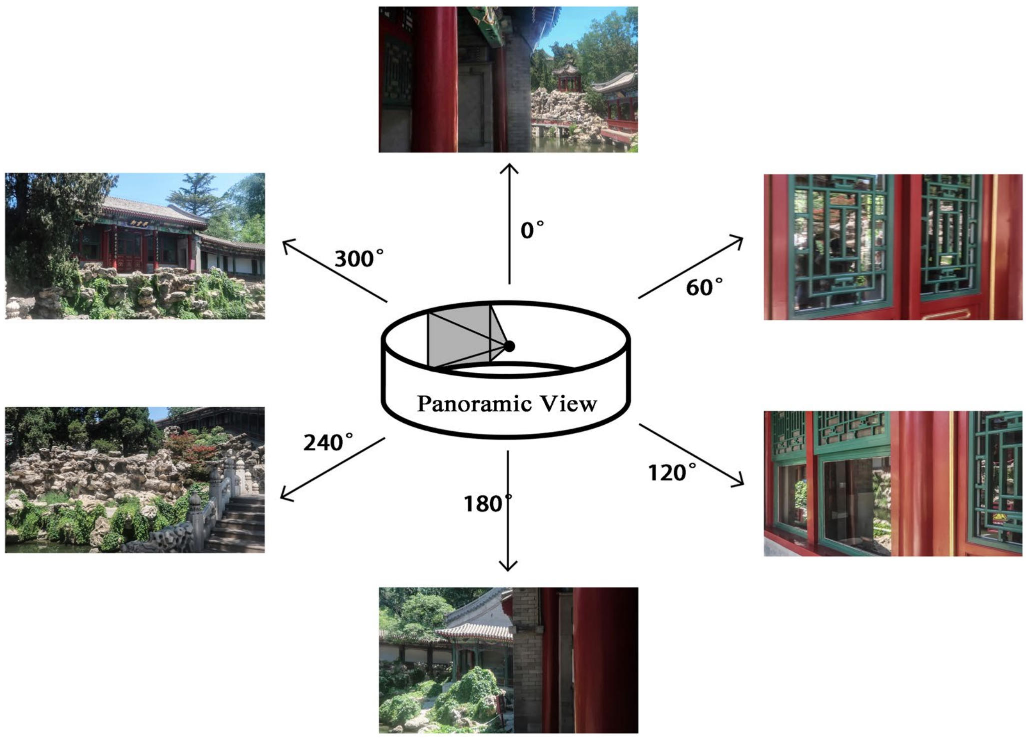


Fig. 3 Illustration of sample point sampling perspective

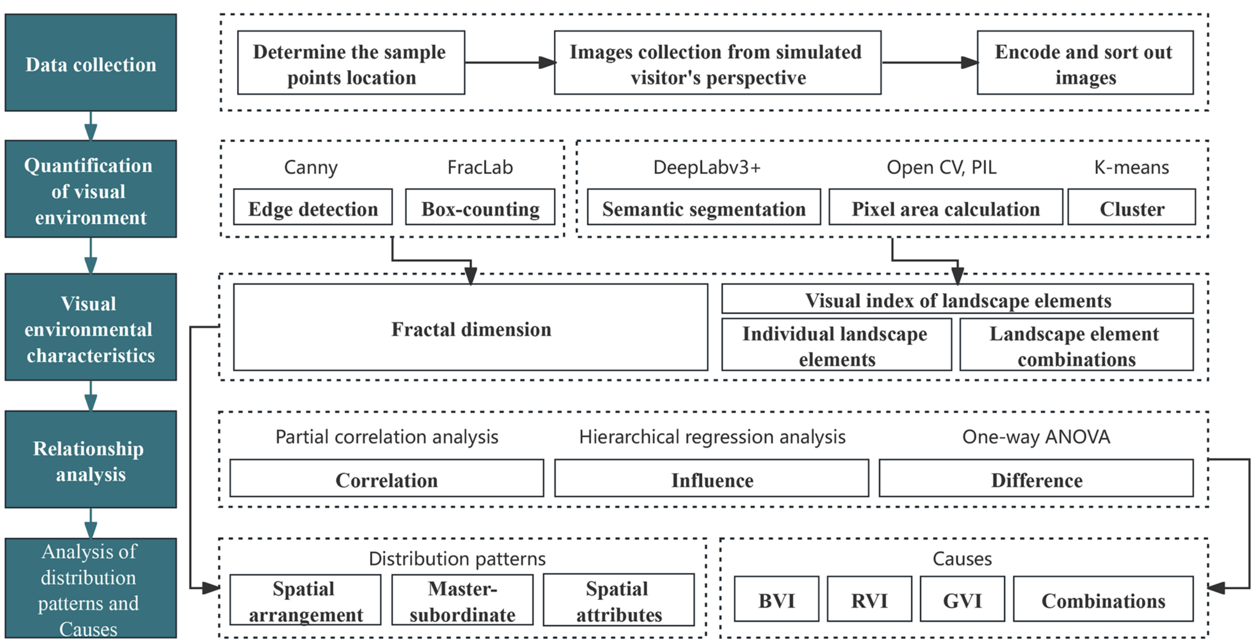


Fig. 4 Research framework

the first-order partial derivative in the vertical direction, $L(i,j)$ represents the gradient magnitude, and $\theta(i,j)$ represents the gradient direction.

Then, non-maximum suppression is applied along the gradient direction. This means that only the pixel with the maximum gradient value is kept, while the other pixels are suppressed, making the edges clearer.

Finally, a double threshold is used to determine the edge pixels, and a high threshold and a low threshold are set. Pixels with gradient values between the low and high

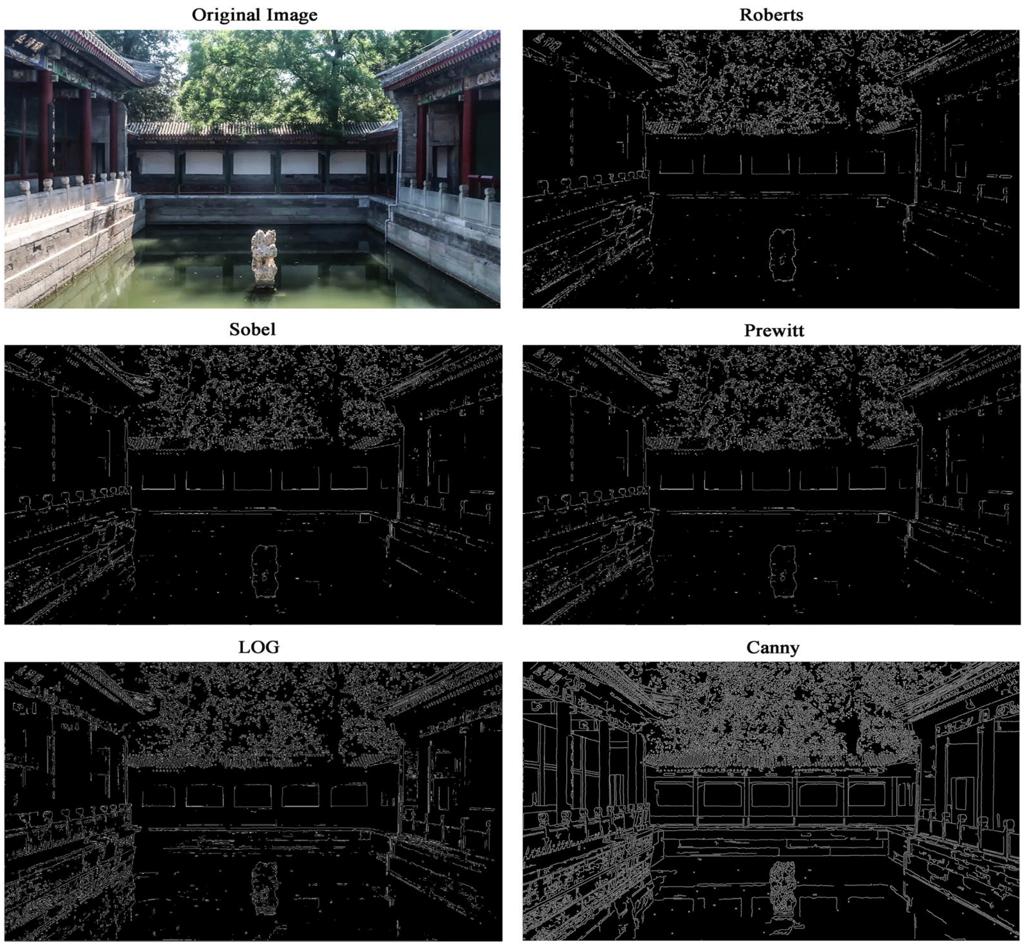


Fig. 5 Comparison of edge detection algorithms

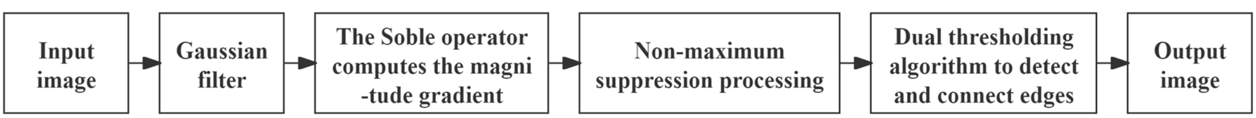


Fig. 6 Canny algorithm flowchart

thresholds are considered weak edge points. Pixels with gradient values above the high threshold are considered strong edge points.

Fractal dimension calculation based on box-counting dimension

In the current research, commonly used fractal dimension algorithms include Hausdorff dimension, box-counting dimension, self-similarity dimension, and topological dimension. The box-counting dimension is commonly employed in built environment research due to its intuitiveness [33]. In this study, the box-counting dimension in FracLab 2.2① was used to calculate the fractal dimensions of the images of Jingxinzhai Garden in the Matlab R2020b (MathWorks Inc., Massachusetts, NY, USA) environment. To ensure the accuracy of the box-counting dimension calculation, the images were preprocessed with binary processing and edge detection, and parameters such as size and fitting method were set.

In the box-counting dimension, an image is divided into multiple boxes of the same size, and then the coverage area of the image contained in these boxes is calculated. By continuously changing the size of the boxes, a relationship between the coverage area and the box size can be obtained. The box-counting dimension is used to describe the fractal characteristics of the image based on this relationship. The calculation formula is:

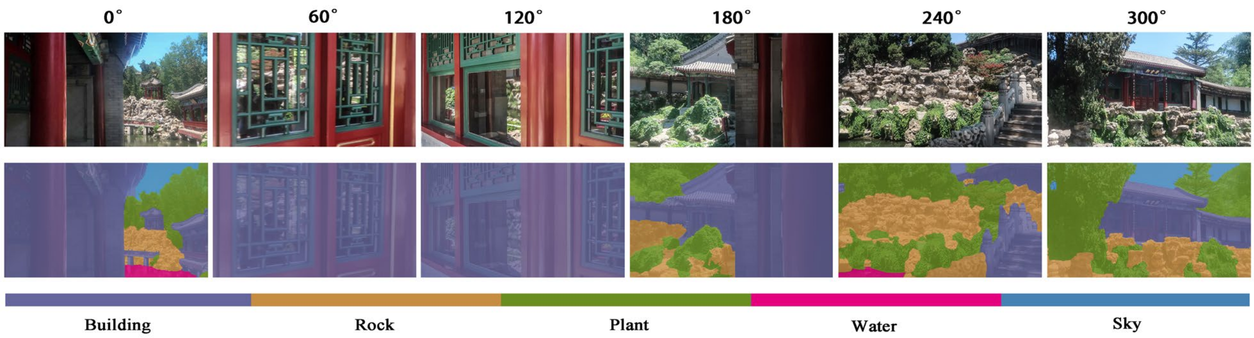


Fig. 7 Semantic segmentation results of sample point images

$$D(O) = \lim_{\varepsilon \to \infty} \left(\frac{\log N(\varepsilon)}{\log(1/\varepsilon)} \right) \quad (6)$$

In the formula, O represents the 2-dimensional object being measured, ε represents the width of the square boxes that cover the fractal set, and N(ε) represents the number of non-empty boxes of width ε needed to cover the set. In general, the larger the box-counting dimension, the more complex the fractal structure of the object, and the higher the visual complexity.

Calculation of visual index of landscape elements

Traditional methods of manually extracting landscape elements in classical gardens are often time-consuming and imprecise. Semantic segmentation is a computer vision technology based on Convolutional Neural Networks (CNNs) that can classify input images at the pixel level [30]. Frameworks such as FCN, SegNet, PSPNet, and DeepLabv3 + are often used in urban street views semantic segmentation research [31, 32]. The DeepLabv3 + has strong versatility and applicability, using techniques such as Dilated Convolution and Atrous Spatial Pyramid Pooling to effectively capture information at different scales in images, thereby improving the accuracy and robustness of semantic segmentation. Compared to other models, DeepLabv3 + performs better in handling multi-scale information. The four key landscape elements of classical Chinese gardens are buildinga, rocks, plants, and water [4].Therefore, The study utilised the DeepLabv3 + model, which was trained on the ADE20K ② dataset [33], to precisely identify these landscape elements in images of Jingxinzhai Garden. Then, to further improve the accuracy of landscape element segmentation, this study used Photoshop (Adobe Inc., San Jose, CA, USA) to manually correct inaccurate local recognition (Fig. 7). Finally, calculate the pixel area and proportion of each landscape element using methods in the OpenCV ③ and PIL ④ to obtain the numerical value of visual index of landscape element.

Data analysis

This study employed SPSS 26.0 (IBM Corp., Armonk, NY, USA) for data analysis and utilized ArcGIS 10.8 (ESRI Inc., Redlands, CA, USA) and Adobe Photoshop for visualizing the data analysis results. The procedures are as follows:

(1) Partial correlation analysis was conducted to determine the correlation between the fractal dimension and the visual index of landscape elements.
(2) Hierarchical regression analysis was utilized to assess the influence of the visual index of landscape elements on the fractal dimension.
(3) The K-means algorithm was used to ascertain the landscape element combinations in the Jingxinzhai Garden. One-way analysis of variance (ANOVA) was conducted to investigate the differences in fractal dimensions among different landscape element combinations.

Results

Spatial distribution of fractal dimensions

Descriptive statistical analysis was performed using SPSS, and the results are shown in Table 1. The mean fractal dimensions of five courtyards are ranked from high to low as BC, EC, WC, FY, and BR. The BC has the highest mean fractal dimension (1.801), indicating that it provides a greater visual complexity compared to other courtyards. On the contrary, the visual complexity received by visitors in the BR is the lowest (Fractal dimension = 1.793). The WC and EC exhibit similar mean fractal dimensions (1.797), suggesting that the visual complexity experienced by visitors in both courtyards is basically same.

To further understand the distribution of visual complexity in the Jingxinzhai Garden tour route, the study visualized the mean fractal dimensions of the sample points (Fig. 8) and counted the number of sample points in different visual complexity intervals (Fig. 9). The tour route of the FY mainly consist of medium and medium

Table 1 Descriptive statistical analysis of fractal dimension in courtyards

Title	Item	Courtyards					Total
		FY	WC	EC	BC	BR	
Fractal dimension	*n*	32	32	42	99	106	311
	Mean	1.795	1.797	1.797	1.801	1.793	1.797
	Standard deviation	0.014	0.015	0.015	0.016	0.011	0.014
	Minimum	1.771	1.760	1.762	1.758	1.771	1.758
	Maximum	1.823	1.821	1.825	1.830	1.827	1.830
	Median	1.793	1.799	1.799	1.803	1.789	1.795

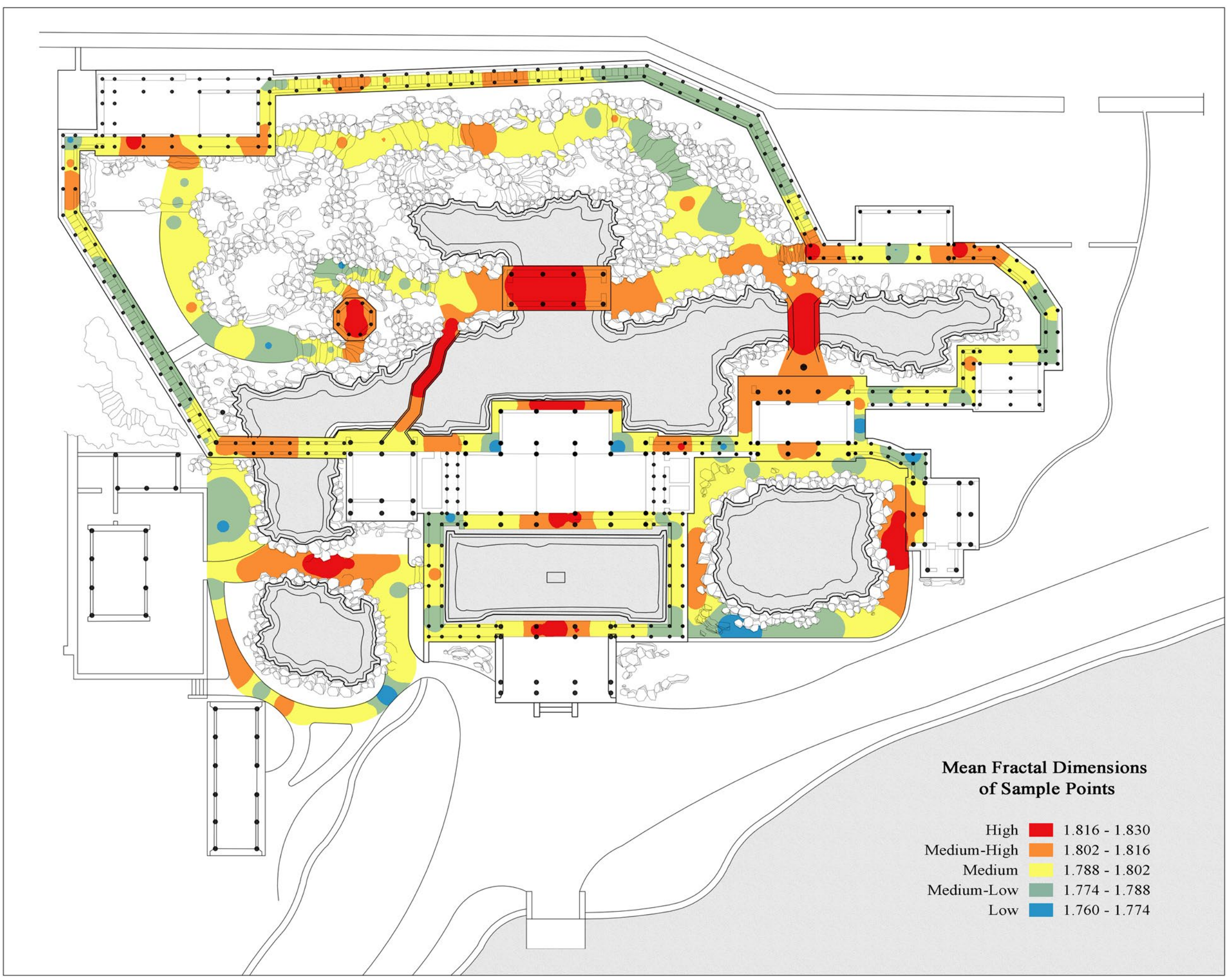


Fig. 8 Distribution of mean fractal dimensions in the Jingxinzhai Garden

low visual complexity areas (accounting for a total of 75%), and the high and medium high visual complexity area in the FY mainly appears at the entrance, as well as the middle of the north corridor. The tour routes of the WC and EC not only have similar mean fractal dimensions, but also have similar proportions in different visual complexity intervals. The high visual complexity area concentrates on the path in the middle of the pool in the WC and on the west side of Yunqin Room in the EC (accounting for 9.4% and 7.0% respectively), and the medium high and medium visual complexity areas are distributed around the pool (accounting for 28.1%

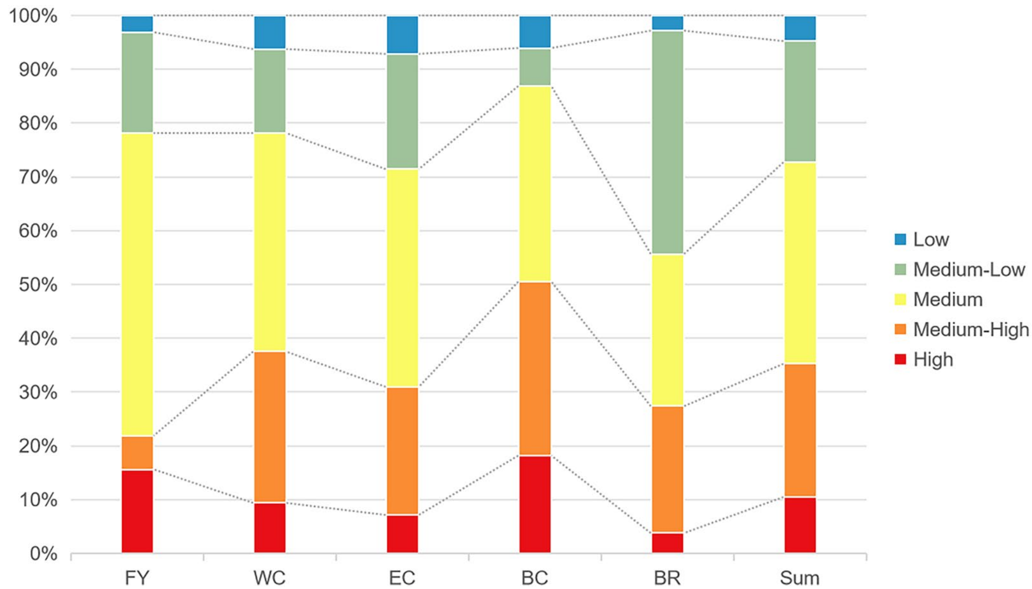


Fig. 9 Proportions of visual complexity intervals in courtyards

(WC), 23.3% (EC) and 40.6% (WC), 41.9% (EC) respectively). The proportion of high and medium high visual complexity areas in the BC is the highest of the courtyards, accounting for 19.8% and 31.7%. The high visual complexity area in the BC appears on Qinquan Pavilion, the north side of the main hall of Jingxinzhai, Qingshi Curved Bridge, and Yundai Bridge. The BR exhibits mainly medium low and medium visual complexity, accounting for 40.2% and 31.8%, respectively. The high and medium high visual complexity areas in the BR are primarily located on Zhenluan Pavilion and the southern side of Diecui Building.

Spatial distribution of visual index of landscape elements

Spatial distribution of visual index of individual landscape elements

The descriptive statistical analysis results of the visual index of individual landscape elements in the Jingxinzhai Garden tour route are shown in Table 2. Overall, the mean Buildings Visual Index (BVI) is the highest (0.298), which is because Chinese classical gardens often use corridors to connect buildings and organize route, resulting in the facades of corridors and buildings occupying a large part of the visitor's visual field during the tour. The mean Water Visual Index (WVI) is the lowest (0.092), which is because the water in the Jingxinzhai Garden exists in the form of pools and is located below the visitor's range of vision, so it occupies a small area in the visual field.

From the descriptive statistical analysis results of courtyards, the BVI (0.630) in the tour route of the FY is significantly higher compared to other visual index of landscape elements, which is consistent with its spatial composition dominated by main gate, the main hall of Jingxinzhai, and Chaoshou Corridors. The tour route in the WC and EC show a similar structure of visual index of landscape elements, with Green Visual Index (GVI), BVI, Rock Visual Index (RVI), and WVI ranked from high to low. Although both the BC and the BR belong to the back courtyard, there are significant differences in the structure of visual index of landscape elements in their respective tour route. The mean visual index of landscape elements in the BC's tour route range from high to low as follows: BVI (0.362), GVI (0.206), RVI (0.193), and WVI (0.122). Nevertheless, along the tour route of the BR, the mean visual index of landscape elements are arranged in descending order as follows: RVI (0.373), BVI (0.204), GVI (0.190), and WVI (0.052).

The visualization results of the mean visual index of individual landscape elements are shown in Fig. 10. High values of BVI appear in the FY, medium values mainly appear in the BC, and low values mainly appear in the WC, EC, and BR. The high values of RVI appear in the BR, while the FY becomes a low-value area for RVI because, except for a stone peak in the center of the pool, there are no other rock arrangements. The high values of GVI are mainly distributed in the WC and EC, while the low values are mainly found in the FY. The high values of WVI are distributed more scatteredly, while the low values are mainly found in the rock path of the BR, which is due to the lack of pool distribution in the BR.

Table 2 Visual index of individual landscape elements in courtyards

Title	Item	Courtyards					Total
		FY	WC	EC	BC	BR	
	n	32	32	42	99	106	311
BVI	Mean	0.630	0.204	0.207	0.362	0.204	0.298
	Standard deviation	0.120	0.021	0.053	0.054	0.037	0.123
	Minimum	0.326	0.158	0.141	0.166	0.152	0.141
	Maximum	0.799	0.243	0.521	0.527	0.371	0.799
	Median	0.659	0.206	0.201	0.358	0.189	0.237
RVI	Mean	0.016	0.149	0.147	0.193	0.373	0.225
	Standard deviation	0.013	0.029	0.036	0.022	0.055	0.110
	Minimum	0.005	0.106	0.107	0.162	0.271	0.005
	Maximum	0.055	0.225	0.337	0.234	0.505	0.505
	Median	0.009	0.148	0.147	0.182	0.367	0.184
GVI	Mean	0.108	0.498	0.489	0.206	0.190	0.259
	Standard deviation	0.027	0.044	0.071	0.025	0.019	0.112
	Minimum	0.069	0.408	0.212	0.029	0.162	0.029
	Maximum	0.180	0.610	0.566	0.241	0.226	0.610
	Median	0.096	0.493	0.492	0.204	0.185	0.204
WVI	Mean	0.099	0.101	0.108	0.122	0.052	0.092
	Standard deviation	0.043	0.034	0.033	0.035	0.025	0.044
	Minimum	0.043	0.039	0.051	0.004	0.000	0.000
	Maximum	0.180	0.157	0.165	0.186	0.096	0.186
	Median	0.079	0.108	0.102	0.123	0.057	0.084

Spatial distribution of landscape element combinations

Compared to individual landscape elements, analyzing interrelationships between various landscape elements can further summarize the typical element combinations and spatial distributions within the Jingxinzhai Garden, leading to a more comprehensive and integrated understanding of the overall layout and features of the garden. The study classified the samples with the help of K-means algorithm based on BVI, RVI, GVI and WVI (Fig. 11) and, based on the elbow rule, identified five typical landscape element combinations in the Jingxinzhai Garden (Table 3), with respective proportions of 23.151%, 13.826%, 32.780%, 0.090%, and 21.222%. From a spatial perspective, combination 1 is mainly found in the WC and EC, combinations 2 and 5 are mainly found in the BC, combination 3 is mainly found in the BR and combination 4 is mainly found in the FY.

Relationship between visual index of individual landscape elements and fractal dimension

Correlation between visual index of individual landscape elements and fractal dimension

To eliminate the interference of control variables, the study used partial correlation analysis to explore the relationship between the visual index of individual landscape elements and fractal dimension. As shown in Table 4, BVI, RVI, and GVI are significantly positively correlated with fractal dimension ($p < 0.05$), which means that the larger the area of buildings, rocks, and plants in the visual field, the higher the fractal dimension, and the higher the visual complexity perceived by visitors. WVI is significantly negatively correlated with fractal dimension ($r = -0.428$, $p < 0.01$), which means that the larger the area of water in the visual field, the lower the fractal dimension, and the lower the visual complexity perceived by visitors.

Influence of visual index of individual landscape elements on fractal dimension

This study used fractal dimension as the dependent variable and did hierarchical regression analysis on courtyards and visual index of individual landscape elements. Model 1 (Table 5) used courtyards as the independent variable, and the R-square value was 0.022, which meant that courtyards explained 2.2% of the variation in fractal dimension. Moreover, model 1 passed the F test ($F = 7.190$, $p < 0.01$), indicating that courtyards had an influence on fractal dimension. Model 2, which added BVI, RVI, GVI, and WVI to model 1, showed a significant change in F value ($p < 0.01$), and the R-square value

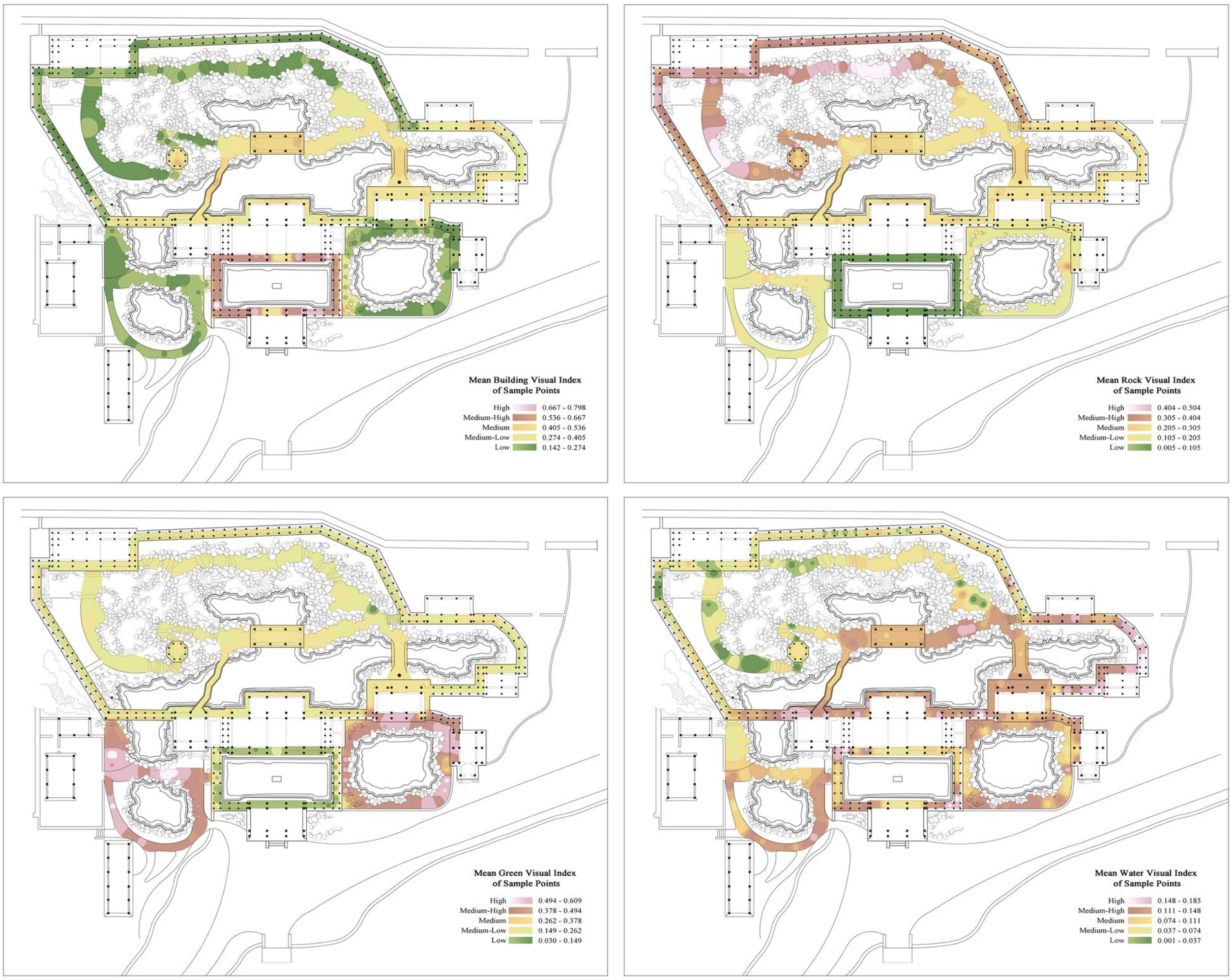


Fig. 10 Distribution of visual index of individual landscape elements in Jingxinzhai Garden

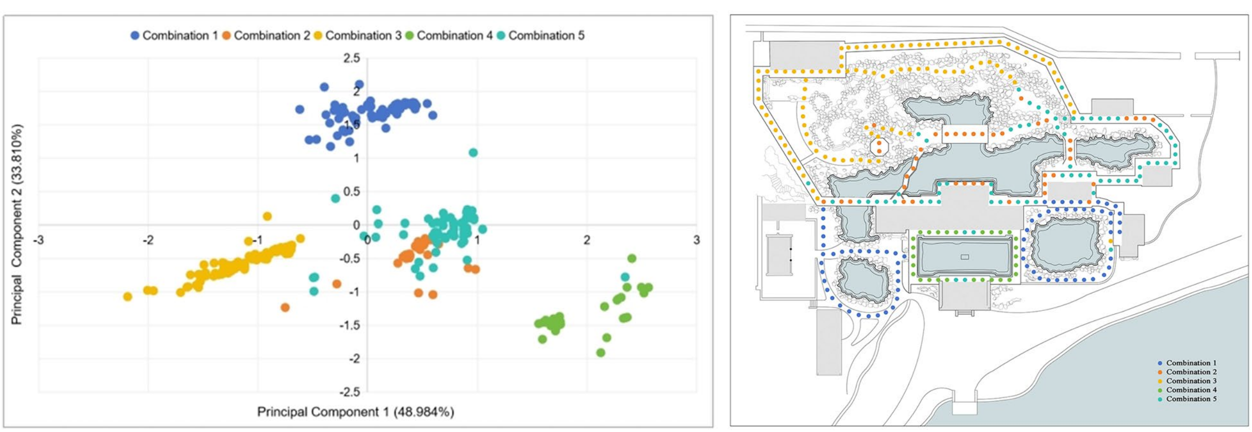
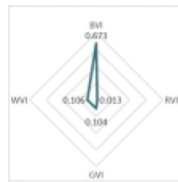
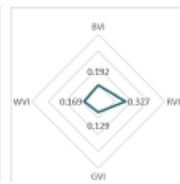


Fig. 11 Scatter plot of clustering of landscape element combinations

Table 3 Characteristic portraits of landscape element combinations in the Jingxinzhai Garden

	Clustering combination (mean ± standard deviation)					F	P
	Combination 1(n = 72)	**Combination 2(n = 43)**	**Combination 3(n = 102)**	**Combination 4(n = 28)**	**Combination 5(n = 66)**		
BVI	0.201 ± 0.02	0.413 ± 0.041	0.201 ± 0.03	0.673 ± 0.04	0.192 ± 0.031	1497.53	0.000***
RVI	0.146 ± 0.024	0.218 ± 0.025	0.374 ± 0.054	0.013 ± 0.009	0.327 ± 0.037	724.246	0.000***
GVI	0.502 ± 0.041	0.222 ± 0.017	0.192 ± 0.022	0.104 ± 0.024	0.129 ± 0.043	1720.503	0.000***
WVI	0.105 ± 0.033	0.1 ± 0.02	0.053 ± 0.025	0.106 ± 0.041	0.169 ± 0.035	65.492	0.000***
Characteristic portraits	low BVI—medium low RVI—high GVI—medium WVI	medium BVI—medium RVI—medium low GVI—medium WVI	low BVI—medium high RVI—medium low GVI—medium low WVI	high BVI—low RVI—low GVI—medium WVI	low BVI—medium high RVI—low GVI—high WVI		
							
Sample images							

* p < 0.1 ** p < 0.05 *** p < 0.01

Table 4 Partial correlation analysis of visual index of individual landscape elements and fractal dimension

	BVI	RVI	GVI	WVI
Fractal dimension	0.340**	0.336**	0.327**	− 0.428***

* p < 0.1 ** p < 0.05 *** p < 0.01

increased from 0.022 to 0.370, indicating that these visual environmental characteristics could explain 34.8% of fractal dimension. Table 5 demonstrates that BVI, RVI, and GVI have significant positive influence on fractal dimension (p < 0.01), but WVI does not have an influence relationship with fractal dimension (p > 0.1). By comparing the standardized coefficients β, it can be seen that the influence of BVI (β = 0.683), RVI (β = 0.588), and GVI (β = 0.439) on the fractal dimension decreases in turn.

Table 5 Hierarchical regression analysis results of visual index of individual landscape elements and fractal dimension

	Model 1					Model 2				
	B	**Standard error**	***t***	***p***	***β***	***B***	**Standard error**	***t***	**p**	**β**
Constant	1.802***	0.002	896.986	0.000	–	1.737***	0.007	244.770	0.000	–
Courtyards	− 0.002***	0.001	− 2.681	0.008	− 0.150	− 0.002***	0.001	− 4.057	0.000	− 0.213
BVI						0.096***	0.008	11.582	0.000	0.683
RVI						0.096***	0.010	9.588	0.000	0.588
GVI						0.078***	0.007	10.851	0.000	0.439
WVI						− 0.036	0.019	− 1.886	0.060	− 0.110
R-squared	0.022					0.370				
Adjusted R-squared	0.019					0.360				
F-value	F (1313) = 7.190, *p* = 0.008					*F* (5309) = 36.303, *p* = 0.000				
ΔR-squared	0.022					0.348				
ΔF-value	F (1313) = 7.190, *p* = 0.008					*F* (4309) = 42.625, *p* = 0.000				

Dependent variable: Fractal dimension

* p < 0.1 ** p < 0.05 *** p < 0.01

Differences in fractal dimension of landscape element combinations

As shown in the results of the one-way ANOVA in Table 6, the mean fractal dimensions for combinations 1, 2, 3, 4, and 5 are: 1.796, 1.813, 1.794, 1.791, and 1.794, respectively. As the assumption of homogeneity of variance was not met, Welch's ANOVA was used instead. The results show that there are significant differences in fractal dimension among different landscape element combinations ($p<0.01$). The fractal dimension of combination 2 is significantly higher than that of the other combinations, with a value of 1.813 ± 0.011. This suggests that the landscape element combination of "medium BVI—medium RVI—medium low GVI—medium WVI" leads to a higher level of visual complexity. In contrast, the fractal dimension of combination 4 is lower than that of the other combinations, with a value of 1.791 ± 0.010, suggesting that the landscape element combination of "high BVI—low RVI—low GVI—medium WVI" leads to a lower level of visual complexity.

Discussion

Spatial distribution patterns of visual complexity

As mentioned in Sect. 3.1, this study measured the fractal dimensions of the tour route in the Jingxinzhai Garden to find that the distribution of visual complexity is uneven, with some degree of clustering and dispersion. This distribution result in dynamic changes in visual perception during the tour, creating the impression of "scenes changing as steps move". The study found that the spatial distribution of visual complexity along the tour route in the Jingxinzhai Garden had the following patterns:

(1) The visual complexity distribution is affected by the spatial arrangement of the garden. In the Jingxinzhai Garden, the Qinquan Pavilion, which spans the water, and the main hall of Jingxinzhai and the main gate form the north–south central axis, so the visual complexity exhibits a subtle and not strictly symmetrical distribution (Fig. 12). The visual complexity of the FY is basically symmetrical along the central axis. The WC and EC on both sides of the central axis not only have a balanced layout in the garden, but also have similar values and characteristics in terms of mean fractal dimension and the structure of each visual complexity intervals. The Yundai Bridge and the Qingshi Curved Bridge flanking the central axis of the BC also present a close visual complexity.

(2) The mean visual complexity in courtyards is affected by the master-subordinate relationship of the courtyards. In Chinese classical gardens, which are composed of several courtyards, different visiting experiences are often created by controlling the visual complexity and other means to distinguish the primary and secondary courtyards [4]. The study found that the visual complexity of the courtyards in the Jingxinzhai Garden has a master-subordinate relationship, and the mean fractal dimensions of the five courtyards shows significant differences. Among them, the BC as the main scenic area has the highest visual complexity.

(3) The visual complexity of the stationary spaces is generally higher than that of the motion spaces. The study revealed significant differences in visual complexity among different spatial attributes of garden (Fig. 12). In Jingxinzhai Garden, high and medium high visual complexity areas are found in the tour route of stationary spaces such as the main hall of Jingqingzhai, the Zhenluan Pavilion, and the Qinquan Pavilion, and visitors staying there can observe the scenery outside the space in all directions. Low visual complexity areas are observed in motion spaces such as corridors and pathways, where reduced visual complexity helps visitors focus on their movement direction [34]. Furthermore, bridges in Chinese classical gardens serve not only as motion spaces but also as stationary spaces [35]. Therefore, the Qingshi Curved Bridge and

Table 6 One-way ANOVA results of fractal dimension of landscape element combinations

Variable name	Variable value	Sample size	Mean	Standard deviation	Variance test	Welch's variance test
Fractal dimension	Combination 1	72	1.796	0.020	F = 22.108 P = 0.000***	F = 30.475 P = 0.000***
	Combination 2	43	1.813	0.015		
	Combination 3	102	1.794	0.015		
	Combination 4	28	1.791	0.014		
	Combination 5	66	1.794	0.018		
	Total	311	1.797	0.018		

* p < 0.1 ** p < 0.05 *** p < 0.01

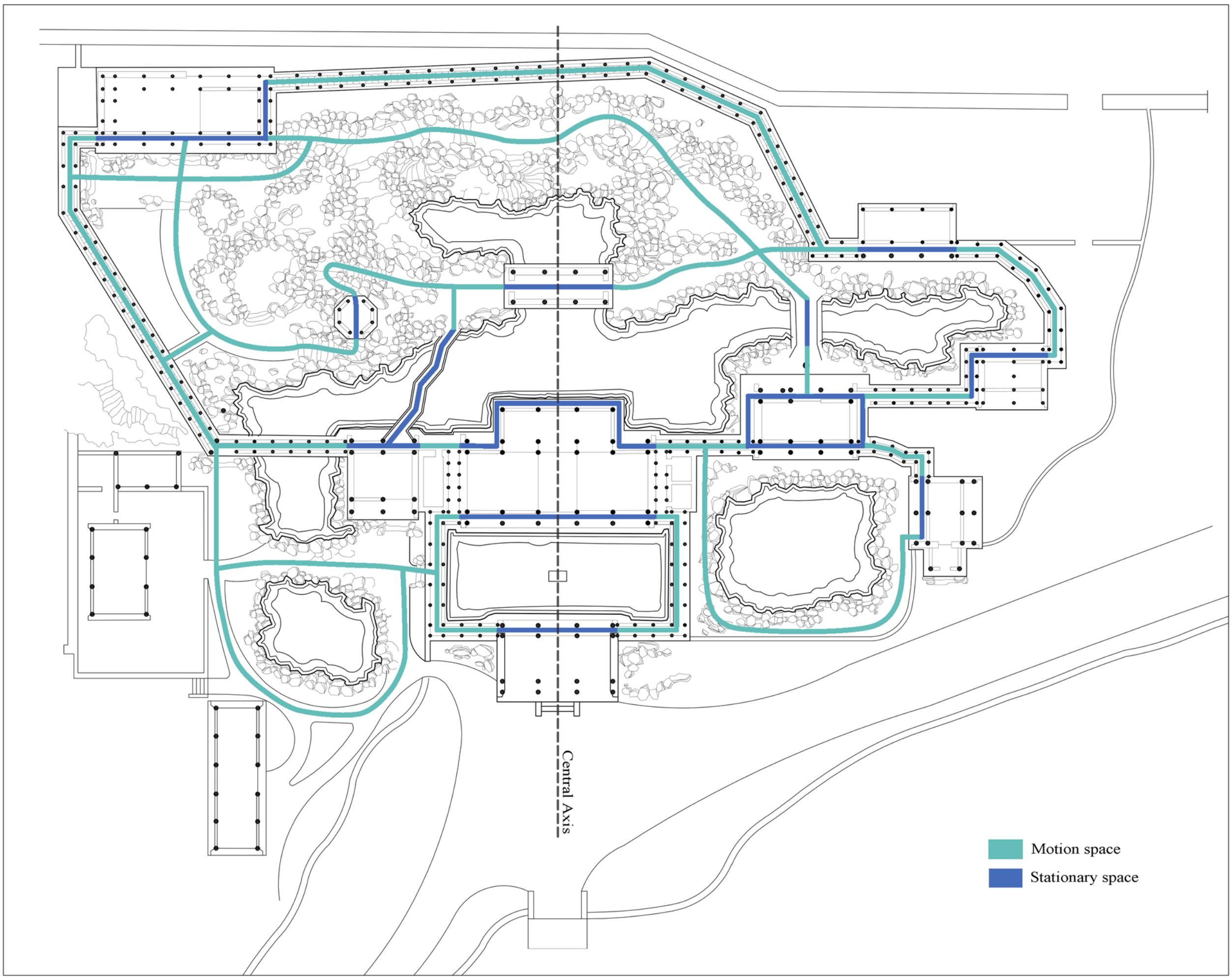


Fig. 12 The central axis and spatial attributes of Jingxinzhai Garde

Yudai Bridge are also considered high visual complexity areas.

Causes of visual environment characteristics in "scenes changing as steps move"

This study explained the phenomenon of "scenes changing as steps move" in garden tours from the perspective of visual environment, revealing variations in visual complexity and visual index of landscape elements at different sample points along the tour route. This implies that as the viewpoint changes, the visual environment perceived by the visitor will also change accordingly. Through the use of partial correlation analysis, hierarchical regression analysis, and one-way ANOVA analysis, the relationships between various visual environmental characteristics were further examined. In order to reveal the underlying mechanism of "scenes changing as steps move", we further discuss and explain the research results based on the characteristics of the design and application of landscape elements in Chinese classical gardens.

(1) BVI is the most significant factor influencing the fractal dimension. The BVI is significantly positively correlated with the fractal dimension ($r = 0.340$, $p < 0.05$), and the BVI has a positive impact on the fractal dimension of the Jingxinzhai Garden ($\beta = 0.683$, $p < 0.05$). The architectural features such as facade, texture, color, height, shape, connection, and decoration have a significant influence on visual complexity [36–38]. The garden architecture of the Ming and Qing dynasties played an important role in creating landscapes, characterized by diverse forms, luxurious decorations, and the intertwining of pavilions, platforms, towers, and buildings with the artificially created landscape [39]. This offers garden visitors a visually abundant and varied environment.

(2) RVI is an important factor influencing the fractal dimension. The RVI is significantly positively correlated with the fractal dimension ($r = 0.336$, $p < 0.05$), and the RVI has a positive impact on the fractal dimension of the Jingxinzhai Garden ($\beta = 0.588$, $p < 0.05$). Rocks adhere to the traditional aesthetic standards of "thinness, wrinkles, cutout and perspective". They pursue the beauty of natural disorder and irregularity [40]. Therefore, their rich and winding edge structures can increase the visual complexity of the garden [41].

(3) GVI is an important factor influencing the fractal dimension. The GVI is significantly positively correlated with the fractal dimension ($r = 0.327$, $p < 0.05$), and the GVI has a positive impact on the fractal dimension of the Jingxinzhai Garden ($\beta = 0.439$, $p < 0.05$). Classical Chinese gardens emphasise the natural shape of plants, in contrast to the neatly trimmed formal garden, and the natural contours of plants, diverse branch forms, and different plant groups all contribute to the visual complexity of the garden [42, 43].

(4) Different landscape element combinations have different influence on visual complexity. There are significant differences in fractal dimension among the five typical combinations of landscape elements in Jingxinzhai Garden ($p < 0.05$). This means that as the landscape element combinations in the view field changes during the visitor's tour, the perceived visual complexity also changes. For BC, there are two landscape element combinations: "medium BVI—medium RVI—medium low GVI—medium WVI" (combination 2) and "Low BVI—Medium–High RVI—Low GVI—High WVI" (combination 5), with mean fractal dimensions of 1.813 and 1.794 respectively. The landscape element combinations with equal emphasis on multiple elements alternately distributed, provides visitors with a visually diversified setting that considerably enhances the accessibility and aesthetic attractiveness of BC.

Limitations and future research

This study has certain limitations. Firstly, the study only focused on the Jingxinzhai Garden, and further validation is needed to generalize the conclusions to other classical gardens. In future research, we will conduct verification studies of multiple gardens in an efficient and batch manner with the help of the computer technology proposed in this study. Secondly, the results of this study show that the regression model cannot fully explain the variation in fractal dimension. Therefore, in terms of data collection, we can combine other approaches such as video recording, VR panoramic images, point clouds, etc., to better capture the complexity and variability of landscape elements. Apart from the four key landscape elements, there may be other important factors that have not been considered, such as lighting, wind direction and strength, cloud cover, etc., which could also impact the fractal dimension and visual index of landscape elements. Future research should more accurately control the visual characteristics of elements in a given scene.

Conclusion

The study effectively measured the visual environment characteristics of Chinese classical garden using computer vision technologies, including FracLab box-counting dimension, Canny edge detection, and DeepLabV3 + semantic segmentation. The relationship between visual complexity and the visual index of landscape elements was analyzed using partial correlation analysis, hierarchical regression analysis, and one-way ANOVA. The results indicated that visual complexity is affected by spatial arrangement, master-subordinate relationship, and spatial attributes. Among the four landscape elements in Chinese classical gardens, BVI, RVI, and GVI have significant effects on the visual complexity of the Jingxinzhai Garden, with BVI being the most significant factor. The Jingxinzhai Garden features five typical landscape combinations, with the combination of "medium BVI-medium RVI-medium low GVI-medium WVI" generating the highest visual complexity.

This study demonstrates the potential contributions of computer vision technology and quantitative methods in the research field of Chinese classical gardens. Through the synergy of image edge detection, box-counting dimension, and image semantic segmentation, this study extends the scale of fractal dimension calculation and landscape element extraction from a few visual images to the entire garden site, laying the foundation for future large-scale visual complexity calculation and research in Chinese classical gardens. In practical terms, future renewal design, conservation, and management of Chinese classical gardens can draw on the results of the research. By integrating the analysis of visual environmental characteristics with current issues such as the openness of the garden and tour routes, adjustments can be made to garden buildings, rocks, plants, water, and element combinations, enhancing the quality and visual effects of landscape.

Notes

① FracLab 2.2 is an open-source software package for fractal analysis and signal processing, with powerful capabilities for calculating fractal dimensions and image processing.

② ADE20K is a large-scale dataset widely used for semantic segmentation tasks, containing images of various scenes and pixel-level semantic annotations.

③ OpenCV is an open-source computer vision library that provides a wide range of image processing and computational functions, including image reading, transformation, feature extraction, and more.

④ PIL (Python Imaging Library) is a Python library for image processing that provides functions for creating, editing, and saving images.

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Author contributions
Conceptualization, Y.C. and Y.G.; methodology, Y.C.and Y.G.; software, Y.L.; validation, Y.G.; formal analysis, Y.C.; investigation, Y.L.; resources, L.C.; data curation, Y.G.; writing—original draft preparation, Y.C.; writing—review and editing, Y.L. and L.C.; visualization, Y.C. and Y.G.; supervision, L.C.; project administration, L.C.; funding acquisition, L.C.. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
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