https://doi.org/10.15302/J-LAF-0-020029 Received Date | 2024-01-02 Accepted Date | 2024-09-24

Research on Spatial Perception in Virtual Historical Streets Based on Eye-Tracking and Physiological Sensing Data

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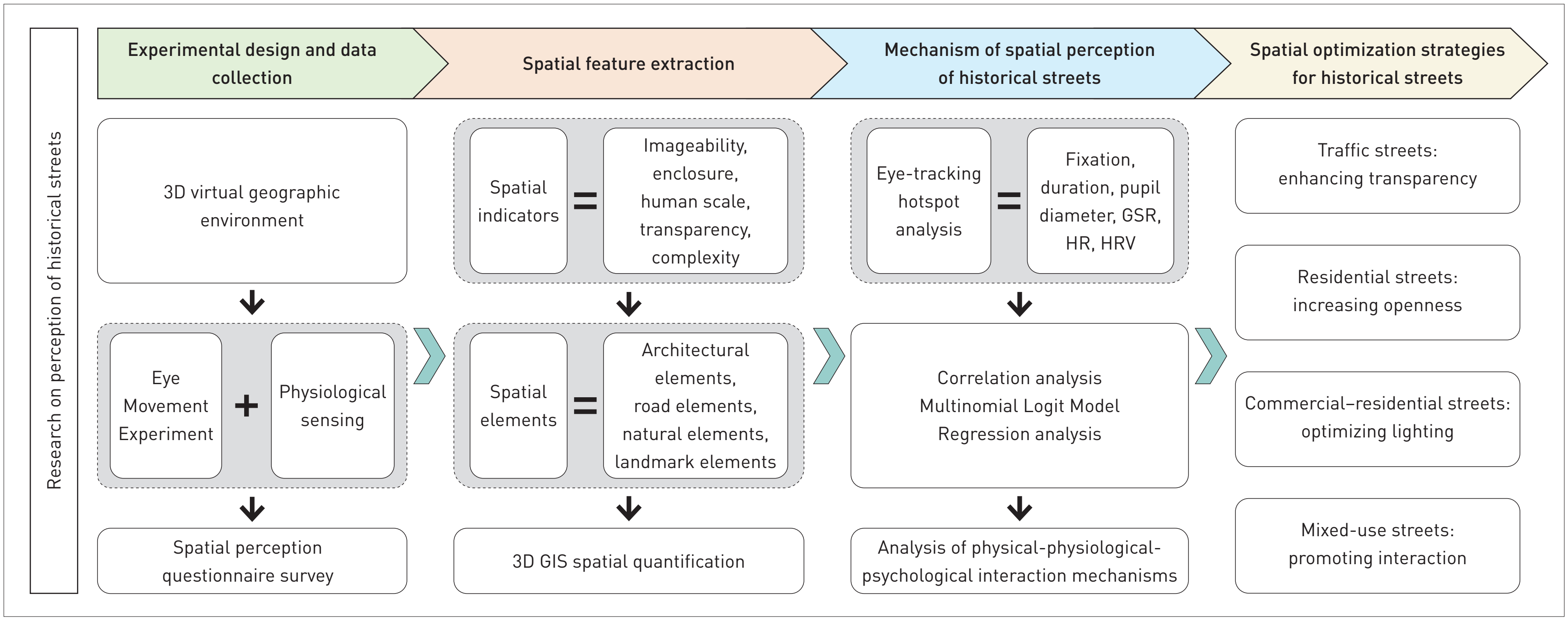
GRAPHICAL ABSTRACT



ABSTRACT

Historical streets are an important component of urban form and embody urban culture. A detailed quantitative analysis of visitors' spatial perception in historical streets is crucial for enhancing the spatial quality of streets. Focusing on Gulangyu Island, Xiamen, this study proposed a physical–physiological–psychological research framework for spatial perception by constructing a 3D virtual geographic environment. Based on environmental behavior theories and five dimensions of street design quality, it assessed the spatial features of historical streets, visitors' eye-tracking and physiological sensing data, and psychological perception, summarized the mechanisms of how historical streetscapes influence visitors' perception, and finally proposed corresponding streetscape optimization strategies. The main findings are as follows. 1) Spatial features of historical streets, including architectural style, layout of commercial spaces, spatial scale, and interface transparency, directly affect visitors' visual experience and preferences. 2) Visual attention is significantly positively correlated with the historical streets' imagery, openness, transparency, and complexity, and significantly negatively correlated with enclosure; among these factors, street openness, vitality, and lighting are key factors influencing visitors' physiological responses. 3) The physical–physiological–psychological interaction mechanisms show that the visual attractiveness and emotional stimulation of the streetscapes can significantly influence individual perception and behavioral decisions, which confirmed the "physical environment–eye-tracking fixation–emotional arousal" mechanism of visitors' visual preferences. Finally, spatial perception optimization strategies for different types of streets are proposed to inform decision-making for historical street renewals.

KEYWORDS

3D Virtual Geographic Environment; Historical Streets; Spatial Perception; Physical–Physiological–Psychological Research Framework for Spatial Perception; Environmental Behavior Theory; Gulangyu Island

HIGHLIGHTS

- Builds a 3D virtual geographic environment for historical street perception with a physical–physio–psych framework
- Architectural style, layout of commercial spaces, and spatial openness affect visual attention and emotions
- Summarizes the physical–physio–psych interaction mechanisms of spatial perception in historical streets

RESEARCH FUND

Project of "Research on Spatial Perception Evaluation and Optimization of Visitors From the Perspective of Heritage Value," National Natural Science Foundation of China General Program (No. 42171219)

EDITED BY Tina TIAN, Yinyu WANG

1 Introduction

With the advancement of urbanization in China, the focus of urban planning has shifted from spatial growth to quality improvement[1]. The built-up environment of historical streets not only has an important influence on visitors' walking behaviors[2], but also embodies local historical memories and cultural characteristics, playing a significant role in heritage conservation and tourism development. However, historical streets are also facing challenges related to functional changes[3], which not only alters the physical environment of the streets but also profoundly impacts visitors' sense of place attachment[4]. Therefore, studying visitors' spatial perception and related influencing factors in historical streets is of great theoretical and practical significance for the organic renewal of historical streets and the enhancement of the tourism experience.

2 Literature Review

Historical streets, as significant cultural heritages, have attracted widespread scholarly attention. Scholars have explored the walkability and visual appeal of historical streets using methods such as virtual reality, eye-tracking, and semantic differential. For example, Cheng Shi et al. used virtual reality and decision tree algorithms to precisely measure walkability, providing practical insights for urban micro-renewal[5]; Zhang Zhang et al. conducted field surveys to reveal the relationship between architectural scale, facade composition, and visitors' walking and stopping behaviors, offering optimization suggestions for historical street design[2]; Yuan Li et al. conducted eye-tracking experiments to analyze the complex relationship between visual appeal and visitors' perceptions of commercial historical streets[6]. There are also studies focusing on using 3D virtual geographic environments and GIS technology for the display and management of historical streets. For instance, Luís Marques et al. proposed a method for 3D modeling and visualization of cultural heritage based on mobile platforms and augmented reality technology[7]; Yu-Pin Ma utilized BIM and 3D modeling to improve the cultural heritage preservation process[8]; Jingxian Tang et al. utilized Tencent street view images, integrating SegNet machine learning with 2D and 3D analysis, to assess the visual quality of hutongs in Beijing, including greenery, openness, and enclosure[9]. Overall, both domestic and international research focuses on the physical representation of historical street environments. Methods like virtual reality and eye-tracking experiments explore human-scale spatial perception and behaviors, providing both theoretical and technical bases for the future protection and optimization design of historical streets.

Environmental psychology theory focuses on the relationship between individuals and the environment, particularly the mechanisms through which environmental factors influence individual psychology[10][11]. In recent years, emerging technologies, such as eye-tracking[12], wearable cameras[13], physiological sensors[14], and virtual reality[15], have enabled environmental psychologists to more accurately and intuitively analyze individuals' visual attention[16], spatial perception[17], and real-time emotional responses to street environments[18], providing strong support for human-scale street renewal design[19].

In research on spatial perception, scholars have examined the spatial perception measurements of streets from multiple perspectives. At the physical level, Reid Ewing and Susan Handy applied expert rating method to measure the quality of urban street design by proposing an evaluation framework consisting of five dimensions: imageability, enclosure, human scale, transparency, and complexity[20][21]. This framework has been widely recognized as a critical tool for assessing and enhancing the quality of urban street design. From a physiological perspective, Zheng Chen et al. integrated spatio-temporal trajectory data with affective parameters, effectively mapping participants' emotional responses to given spaces[18]. This approach provides a new perspective for environmental design research. From a psychological standpoint, eye-tracking technology has been extensively applied in studies on visitors' landscape preferences[22], as well as preferences for environmental elements like street buildings[23]~[25].

With advancements in 3D virtual geographic environments[26][27], machine learning[28][29], and multi-sourced big data[30], researchers can now more easily construct virtual reality experimental settings[31] and perform semantic segmentation of eye-tracking attention elements[6]. These technological developments not only overcome the limitations of previous studies where street perception experiments were often subject to pedestrian-related factors[14][23], but also help generate low-cost, controlled 3D virtual geographic environments[32]. Furthermore, they enable a more detailed representation of historical street features and micro-scale environments[33], supporting behavior modeling[34] and integrated data analysis.

In summary, although existing street perception evaluation methods and the application of new data and technologies have provided valuable insights into the evaluations of historical street perception, there is still a lack of studies that combine eye-tracking and physiological sensing within virtual scenarios of historical streets. Based on environmental behavior theories and the five dimensions of street design quality, this study proposes a research framework of spatial perception in historical streets within a virtual geographic environment. It innovatively integrates eye-tracking technology with virtual reality to precisely capture visitors' visual attention and to explore spatial perception, informing the spatial optimization design of historical streets.

3 Research Methodology

3.1 Research Framework

This study proposed a physical–physiological–psychological research framework for spatial perception on historical streets. At the physical level, spatial attributes and environmental characteristics of historical streets were calculated; five indicators, i.e. imageability, enclosure, human scale, transparency, and complexity, were used to evaluate street spatial features. At the physiological level, eye-tracking and physiological sensing experiments were conducted in a virtual geographic environment; physiological indicators including fixation duration, pupil diameter, galvanic skin response, heart rate, and heart rate variability were collected to analyze the impact of varied spatial factors on perception. At the psychological level, post-experiment evaluations were conducted to analyze participants' detailed perception on different spatial factors, and then, spatial optimization suggestions for historical streets were proposed (Fig. 1).

3.2 Study Area

Gulangyu is an island located in the southwestern corner of Xiamen Island, China, covering an area of approximately 1.88 km^2. The island's road system is primarily composed of 35 historic streets. The streets are famous for their historical characteristics, and visitors primarily experience them on foot[35]. Based on the Historical and Cultural District Protection Plan for Gulangyu Island[35], preliminary field survey results, and relevant studies[36][37], a route that links up the key architectural heritages of Gulangyu at maximum was selected for research. Four street types are included on the route: traffic, commercial–residential, residential, and mixed-use (Table 1, Fig. 2). The total length of the route is approximately 3.5 km, and a virtual tour takes 20 ~ 30 minutes at a normal walking speed.

3.3 Participants

A total of 41 students from Xiamen University were recruited both online and offline as participants for the eye-tracking and physiological sensing experiments. Among them, 73.2% were female and 26.8% were male①. The experiment was conducted at the Xiamen Key Laboratory of Integrated Application of Intelligent Technology for Architectural Heritage Protection from November 22 to 29, 2022. of the participants, 92.7% reported that they had visited Gulangyu

① Most eye-tracking experiments recruited around 30 participants, with only a few studies reaching 60 participants (e.g., Ref. [17]). Therefore, the sample size of this study is considered reasonable and adequate.

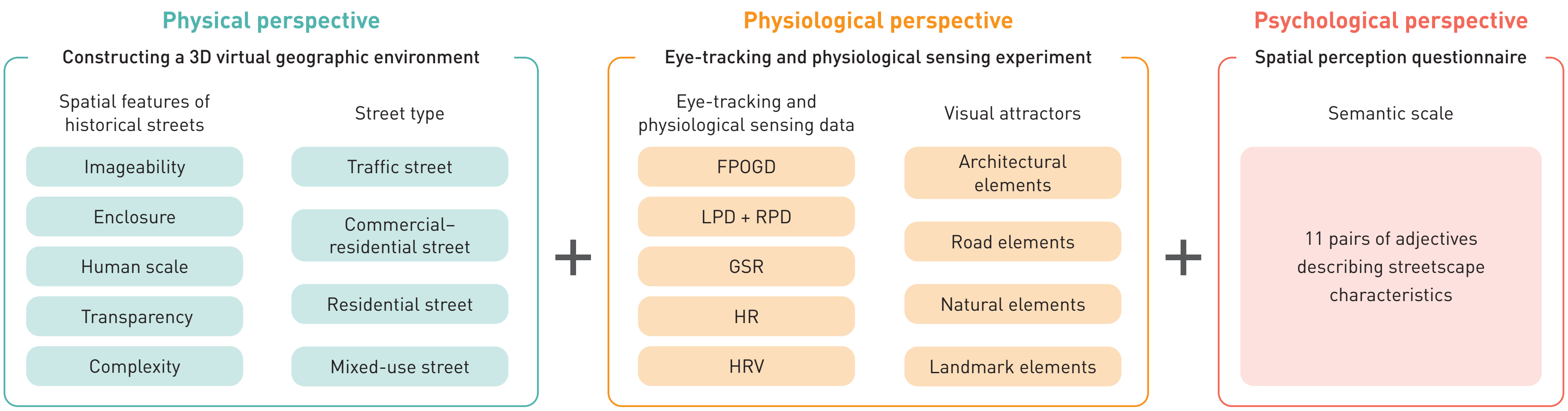


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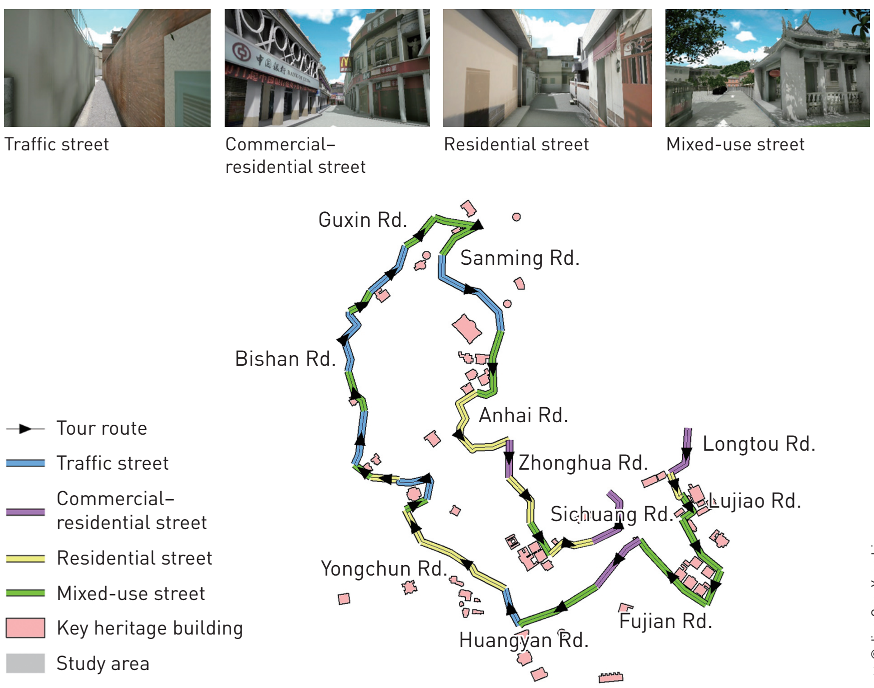
Table 1: Types and characteristics of historical streets in Gulangyu Island

Street type	Characteristics
Traffic	Mostly the narrow linear spaces shaped between buildings' gable walls or fences, primarily connecting different places
Commercial–residential	Often found in densely commercial areas, where streets feature commercial usage on the ground floor and residential spaces on upper floors
Residential	Composed of linear clusters of residential units along both sides of streets
Mixed-use	Streets with a blend of diverse uses (e.g., commercial, residential), including various heritage buildings



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Island before and an analysis of variance (ANOVA) showed that prior visits had no significant impact on the evaluation results. When assessing the virtual scenes' authenticity, participants assigned an average score of 4.09 (out of 5), indicating that the virtual geographic environment in the experiment can effectively replicate the real-world experience in the historical streets of Gulangyu Island (Figs. 3, 4). To eliminate potential interference by visitor images on participants' gaze distribution and psychological perception, ensuring their focus solely on the physical environment, the virtual scenes used in the experiment did not include any depictions of visitors.

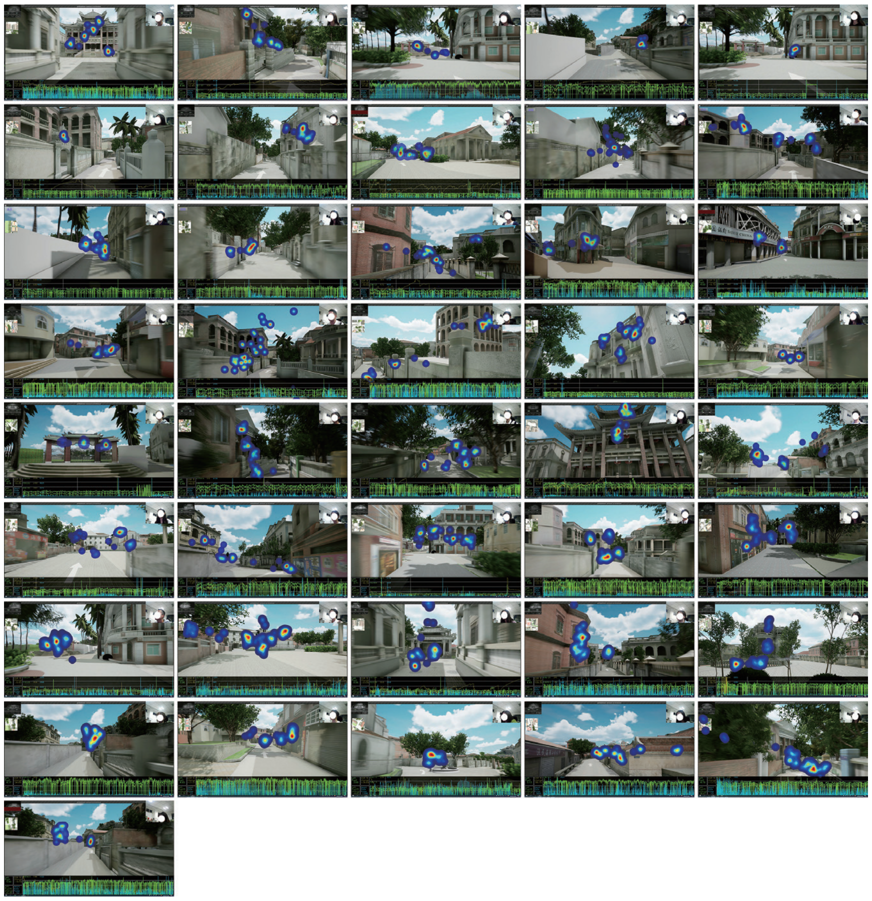
3.4 Multi-Sourced Data Collection and Integration

The experiment utilized a Gazepoint GP3 device to simultaneously collect participants' eye-tracking and physiological sensing data.

Step 1: A 3D virtual geographic environment was built using the Unreal Engine 4 (UE4) game engine[32]. After signing an informed consent and completing eye-tracking calibration, participants conducted a virtual tour along the research route. They filled out a spatial perception questionnaire evaluating their experience in the virtual environment when completing the tour.

Step 2: Following previous studies that use videos and virtual tours as stimulus materials[1][14][38], the collected eye-tracking and physiological sensor data used in this research were segmented into 10-second intervals, recoding changes in spatial coordinates of each segment and plotting eye-tracking heatmaps and physiological indicator variations.

1. Research framework for spatial perception of historical streets.
2. Research route, created based on the standard map from the Xiamen Natural Resources and Planning Bureau, map number Xiamen S [2022] 05.



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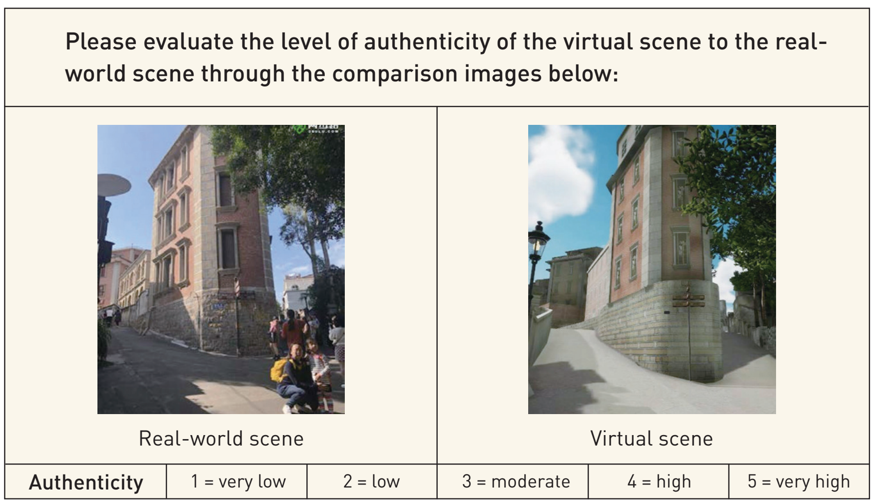

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3. Experimental screenshots of 41 participants.
4. Example of the authenticity assessment of the virtual scenes. In the survey, the scoring criteria ranged from 1 (very low) to 5 (very high).

Step 3: The detailed physical environment of the research route was analyzed by segment using SuperMap's 3D GIS. Additionally, machine learning-based semantic segmentation of streetscape features was performed using the ADE20K dataset, which contains over 27,000 finely annotated images and is widely recognized in academic studies on scene understanding[29][39].

Step 4: Based on the segmented data obtained from Step 2, further statistical processing was conducted on the physiological sensing data. The time window was set to 10 seconds to smooth extreme values, reducing fluctuations and ensuring the accuracy and reliability of the analysis results.

Step 5: All data were integrated into a GIS platform based on a unified spatial coordinate system. The final dataset comprised 8,375 spatial coordinate points, along with their corresponding eye-tracking and physiological sensing data, spatial indicators for each street segment, and participants' responses to the perception questionnaire.

3.5 Indicator Selection and Measurement

3.5.1 Physical Indicators

Based on previous studies[2][20][32][38], the spatial characteristics of the historical streets in the study area, and computational feasibility, this study selected 15 indicators to characterize the spatial elements of historical streets from the five dimensions of street design quality: imageability, enclosure, human scale, transparency, and complexity (Table 2).

3.5.2 Physiological Indicators

Referring to previous studies[18][22][38][40], this study selected the following physiological indicators to identify participants' attention distribution and emotional arousal responses to historical street spatial elements:

1) Fixation points on the objects of interest during gaze duration (FPOGD): The duration time of fixation points on objects of interest, typically measured in milliseconds. This indicator reflects how the human eye allocates attention to objects of interest in the environment.

2) Pupil diameter (LPD for left pupil diameter and RPD for the right): Controlled by the visual nervous system, this is an indicator of visual arousal levels.

3) Galvanic skin response (GSR): The electrical response of the skin to external stimuli. In emotional research, this indicator is commonly used to measure the intensity of emotional arousal.

4) Heart rate (HR) and heart rate variability (HRV): HR refers to the number of heartbeats per unit of time, while HRV indicates the degree of fluctuation between heartbeats over time. Both indicators are widely used to assess emotional arousal levels.

3.5.3 Psychological Indicators

Upon previous research[41], this study adopted a questionnaire to

Table 2: Spatial feature indicators of historical streets

Dimension	Spatial feature indicator	Definition	Calculation method
Imageability	Pedestrian activity level	The degree of human activity in the public space of the street	Statistics from Baidu Map Heatmap
	Proportion of historic buildings	The percentage of historic buildings in the total building count in the study area, where historic buildings refer to the ones constructed in or before the early 20th century	Statistics of construction years of buildings
Enclosure	Street width	The width of the street	Using 3D GIS
	Building height (same side)	The height of buildings on the same side of the street	Using 3D GIS
	Building height (opposite side)	The height of buildings on the opposite side of the street	Using 3D GIS
	Height-to-width ratio (same side)	The ratio of building height to street width on the same side	Using 3D GIS
	Height-to-width ratio (opposite side)	The ratio of building height to street width on the opposite side	Using 3D GIS
	Proportion of sky	The proportion of sky in the field of view	Semantic segmentation of scene screenshots
Human scale	Sky openness	The degree of openness of the sky overhead	Using 3D GIS openness analysis
	Long sightline	The longest length of the visible distance	Using 3D GIS sightline analysis
	Visual field volume	The three-dimensional space in the viewshed	Using 3D GIS visibility analysis
	Visual field area	The two-dimensional area in the viewshed	Using 3D GIS visibility analysis
Transparency	Proportion of wall	The proportion of walls within the viewshed	Semantic segmentation of scene screenshots
Complexity	Proportion of building	The proportion of buildings within the viewshed	Semantic segmentation of scene screenshots
	Environmental color contrast gradient	The color contrast between buildings and their surrounding environment	RGB mean value analysis

NOTES

1. During the virtual tour, the "same side" refers to the right side of the participant's forward direction, while the left side refers to the "opposite side."
2. The terms "three-dimensional space" and "two-dimensional area" are spatial geometric concepts derived from 3D GIS analysis. The former refers to the volumetric spatial extent in the viewshed, enclosed by boundaries such as the ground (building bases), building walls, and rooftops; the latter refers to the horizontally projected area of the viewshed onto a flat plane, primarily indicating the spatial coverage of visibility.

collect psychological perception data on streetscape experiences. The questionnaire employed the semantic differential method commonly used in psychological studies, providing 11 pairs of adjectives to describe various streetscape characteristics. Participants were required to evaluate each item and assign values ranging from −3 to 3, where 0 represents a neutral perception level, −1 and 1 represent a moderate perception level, −2 and 2 represent a strong perception level, and −3 and 3 represent a very strong perception level (Fig. 5).

3.6 Statistical Methods and Models

3.6.1 Spatial Hotspot Analysis

This study employed the Getis-Ord G_i^* method to analyze whether the eye-tracking attention elements and physiological

Please evaluate your perception while touring in the virtual scenes of streetscape.

Semantic differential scale for streetscape perception

	−3	−2	−1	0	1	2	3	
Enclosed								Open
Narrow								Spacious
Lively								Quiet
Crowded								Uncongested
Messy								Clean
Monotonous								Diverse
Dark								Bright
Less greenery								Abundant greenery
Ordinary								Unique
Uneasy								Secure
Highly commercialized								Less commercialized

5. Example of the spatial perception questionnaire.

sensing data exhibit significant spatial clustering. The Getis-Ord G_i^* method is commonly used in spatial hotspot analysis[42], which calculates the values of surrounding elements for each data point (or area) and determines their statistical significance, so as to assess the intensity and location of spatial clustering. The calculation formulas are as follows[43]:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \overline{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j} \right)^2 \right]}{n-1}}}, \tag{1}$$

$$\overline{X} = \frac{\sum_{j=1}^{n} x_j}{n}, \tag{2}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j}{n}}, \tag{3}$$

where x_j represents the attribute value of element j, $w_{i,j}$ denotes the spatial weight between elements i and j, and n is the total number of elements. The result of G_i^* is a z-score, where a significantly positive z-score indicates that higher values (hotspots) are more intensely clustered; conversely, a significantly negative z-score exhibits lower values (coldspots), meaning a higher degree of clustering.

3.6.2 Discrete Choice Model

This study posits that spatiotemporal factors influencing participants' visual attention preference are highly complex. Therefore, a discrete choice model was employed in this research to analyze the impact of physiological feedback on visual selection behaviors. Based on existing literature[44] and data availability, the multinomial logit (MNL) model for participants' visual preference is expressed as follows[45]:

$$P(y=i) = \frac{e^{\beta x}}{\sum e^{\beta x}}, \tag{4}$$

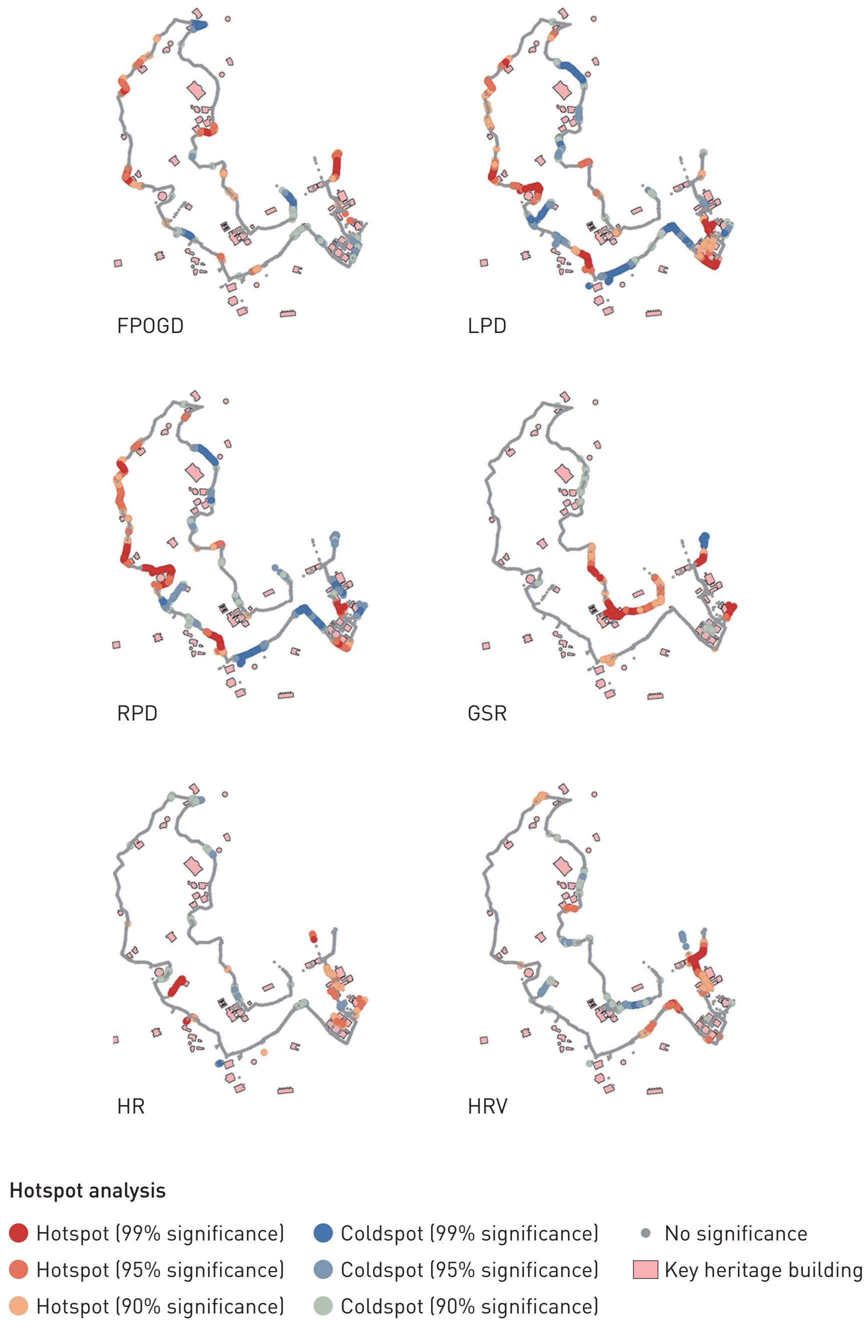
where, the dependent variable y represents the participant's selection for visual element i. Based on eye-tracking heatmap statistics, the output is classified into two mutually exclusive categories (selected or not selected), with corresponding values of 1 or 0. In the multinomial regression analysis, the independent variable x represents the participant's physiological sensing data, which is standardized; and the parameter β denotes the coefficient of the independent variable.

4 Research Results

4.1 Spatial Hotspot Analysis

The analysis results (Fig. 6) indicate that participants had significantly longer fixation durations when touring commercial–residential streets (e.g., Longtou Road, Anhai Road). This suggests that these streets' distinct commercial styles and high-information-density environmental elements (e.g., storefront signage and entrance spaces) effectively captured participants' long-duration visual attention. In contrast, for mixed-use streets like Fujian Road, Sanming Road, and Yongchun Road, the rich historical features and diverse spatial elements (e.g., heritage buildings, courtyards, landmarks) led to more frequent shifts in participants' gaze, resulting in significantly shorter fixation durations.

For residential streets (e.g., Anhai Road) and mixed-use streets (e.g., Fujian Road), a significant increase in PD was closely associated with core impressive spatial elements, such as the blend



6. Physiological data hotspot analysis. Created based on the standard map from the Xiamen Natural Resources and Planning Bureau, map number Xiamen S [2022] 05.

of historical and modern architecture, which provided rich visual stimuli and fostered deep emotional connections for participants. Conversely, for Bishan Road and Guxin Road, which are traffic streets surrounded by greenery, the dimmer ambient lighting and low-lying shrubs tended to draw participants' attention, leading to high-value clustering of PD measurements.

On commercial–residential streets such as Zhonghua Road, Shichang Road, and Longtou Road, participants exhibited a significantly higher GSR. These streets not only include a diverse array of street-front shops and high-density building layouts, but also have brighter lighting and greater visual accessibility, which collectively contribute to a richer visual experience. Similarly, in an eye-tracking study on Nanjing Road, Shanghai, Chen Zheng et al. also revealed how outdoor storefront signage shapes "unique," "rich," and "distinctive" streetscapes that provided strong visual impression for pedestrians[12].

High-value HR and HRV clusters were concentrated around Lujiao Road and Fujian Road. The key heritage buildings in these areas not only captured attention from most participants but also reinforced emotional connections by evoking personal memories and experiences. For example, some participants verbally reported that while touring Fujian Road, they recalled their previous visits to the Haitian-Tanggou Mansion.

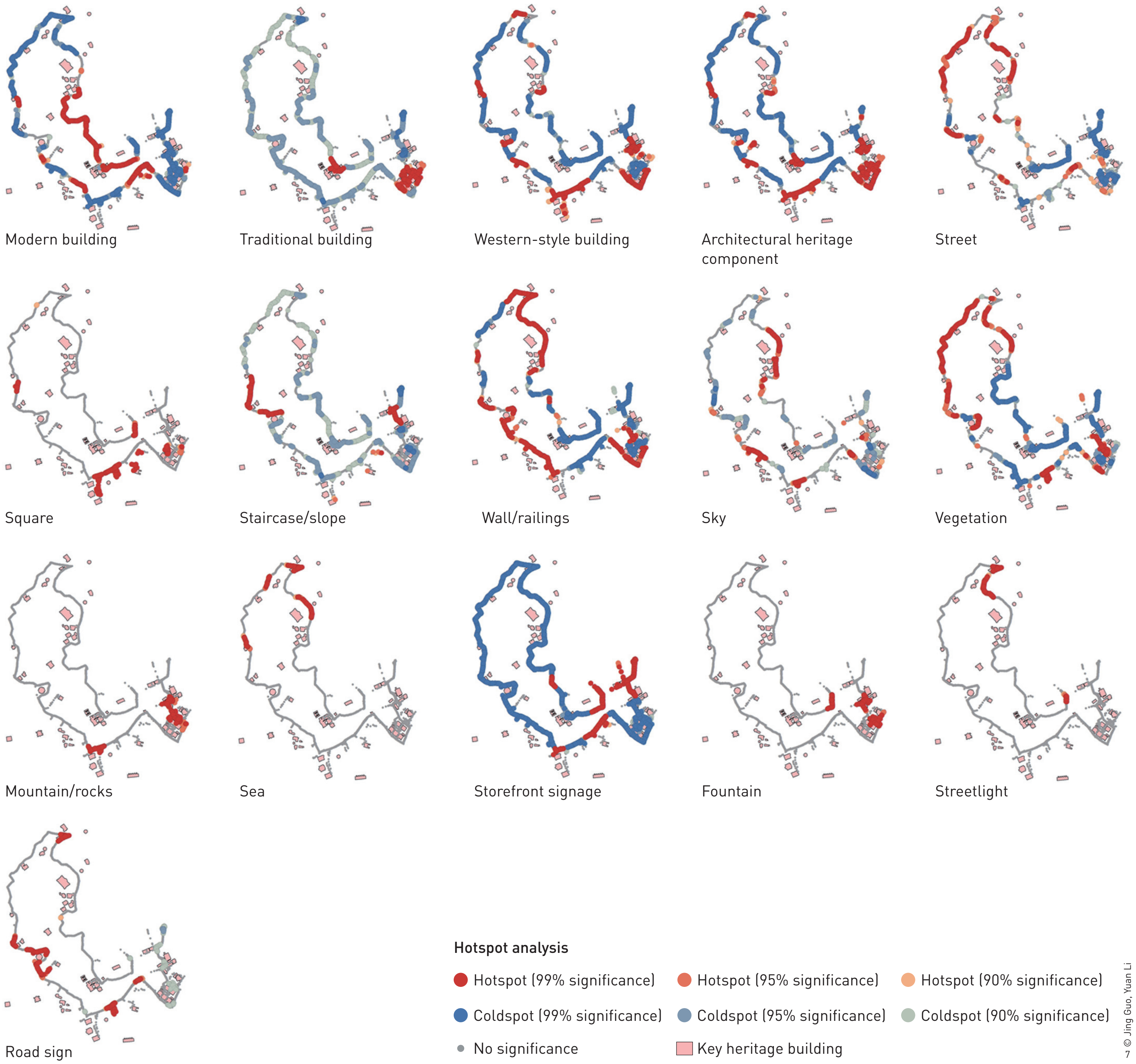
4.2 Spatial Hotspot Analysis of Visual Attractors

Based on relevant literature[46] and the spatial features of historical streets in Gulangyu Island, this study categorized visual attractors in participants' eye-tracking preferences into architectural elements, road elements, natural elements, and landmark elements, comprising a total of 16 subcategories. Among them, architectural elements were further classified into modern building, traditional building, Western-style building, and architectural heritage component, based on their construction period and architectural style[47] (Table 3). Road elements include street, square, staircase/slope, and wall/railings; natural elements consist of sky, vegetation, mountain/rocks, and sea; and landmark elements encompass storefront signage, fountain, streetlight, and road sign.

The spatial hotspot analysis of eye-tracking data (Fig. 7) shows that high-value clusters of architectural elements were primarily concentrated in zones with a higher density of historical buildings, where distinctive architectural styles exerted a strong visual attraction on participants. Road elements exhibited high-value clusters at street intersections and the locations with clearly defined spatial boundaries, where the high visibility and spatial openness allowed participants to pass through or linger, underscoring their importance in pedestrian flow. Natural elements showed high-value clusters in beachfront and park areas, demonstrating the strong visual appeal of natural landscapes to participants. Meanwhile, landmark and iconic elements formed high-value clusters in commercial–residential streets and spatial nodes like the intersection of Guxin Road and Sanming Road, known as the "most beautiful corner on the island."

Table 3: Classification of architectural elements

Street type	Characteristics
Traffic	Built in or after 1941, predominantly featuring modernist architectural styles
Commercial–residential	Southern Fujian traditional residences constructed before the Opium War (before 1840)
Residential	Constructed by overseas Chinese from the late 19th century to the early 20th century, often exhibiting Western revivalist styles or a blend of Chinese and Western architectural elements
Mixed-use	Structural or decorative elements that are designated as part of heritage buildings

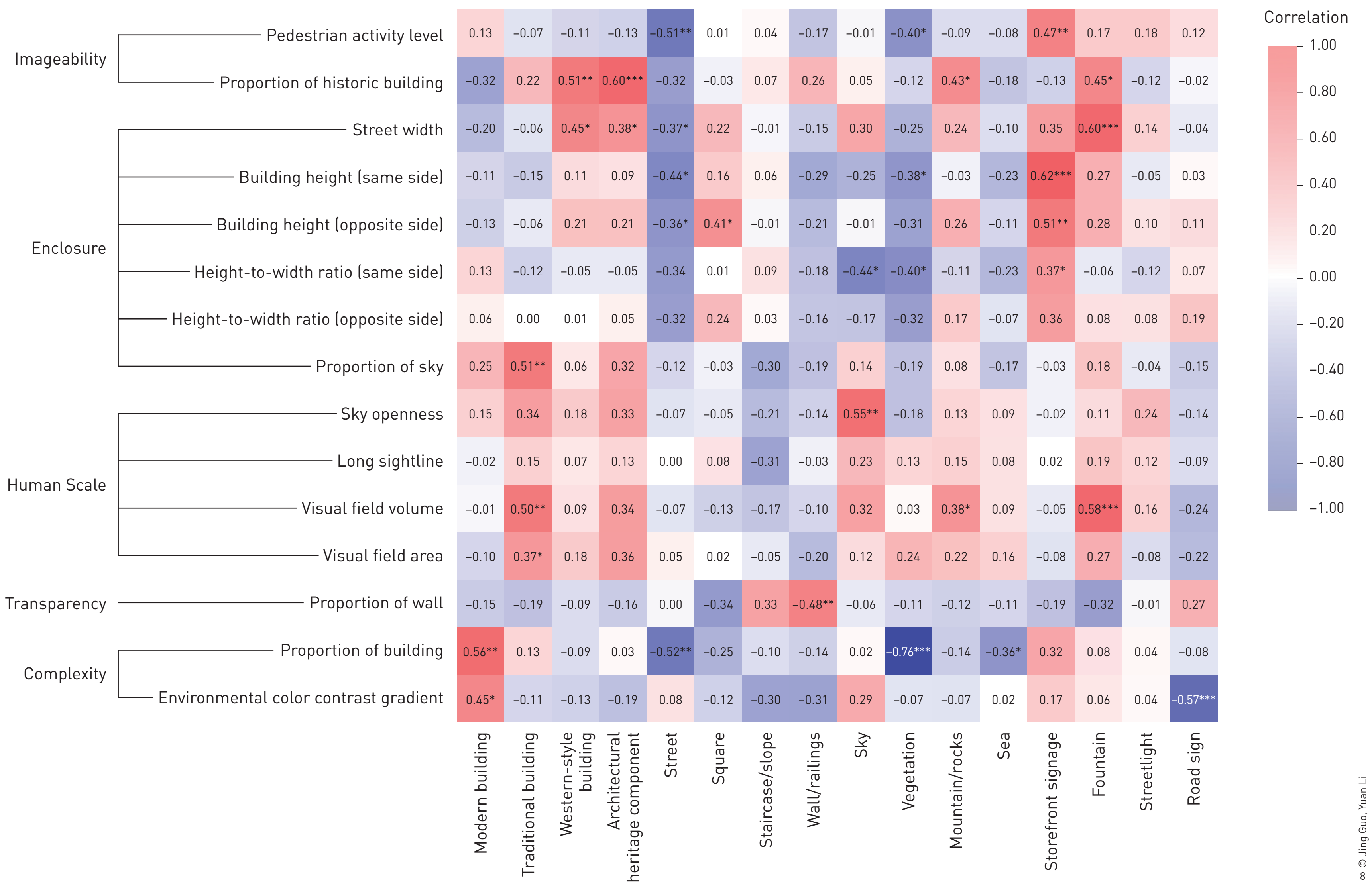


7. Hotspot analysis of eye-tracking visual attention elements, created based on the standard map from the Xiamen Natural Resources and Planning Bureau, map number Xiamen S [2022] 05.

4.3 Correlation Analysis Between Street Spatial Features and Visual Attractors

This study examines the correlation between street spatial features and visual attractors, further revealing the influence of the physical environment on psychological perception (Figs. 7, 8).

1) Imageability: Pedestrian activity level showed a negative correlation with street and vegetation but a positive correlation with storefront signage. Meanwhile, the proportion of historic building was positively correlated with Western-style building, architectural heritage component , mountain/rocks, and fountain. These results suggest that in areas with higher pedestrian dynamics, commercial elements such as storefront signage are more likely to attract participants' visual attention. This is because commercial areas typically feature more interactive spaces and stronger visual stimuli, where visitors are often attracted by advertisements and signage with bright colors and distinctive fashions. This trend was particularly evident in commercial–residential streets such as Longtou Road and Shichang Road. In contrast, streets with a higher proportion of historic buildings, such as Fujian Road and Huangyan Road, became popular focal points for participants due to their rich historical and cultural significance and distinct architectural styles. Western-style buildings and architectural heritage components often have strong historical symbolism, which is particularly prominent in Xiamen—as a city with a unique cultural and historical context, Xiamen's historical sites and buildings exhibit a greater visual appeal, and the fusion of traditional and Western architectural



8. Results of correlation analysis between spatial feature indicators and eye-tracking visual attractors (* indicates significant correlation at the 0.05 level, ** indicates significant correlation at the 0.01 level, and *** indicates significant correlation at the 0.001 level).

styles provides a more diverse visual experience for visitors.

2) Enclosure: Street width showed a positive correlation with Western-style building, architectural heritage component, and fountain, while the height-to-width ratio (same side) was positively correlated with square and storefront signage. The street layout and architectural characteristics significantly influenced participants' visual attention—wider streets would lead to a greater attention to buildings and public spaces, whereas narrower streets would enhance the visual prominence of road elements. For streets with rich heritage buildings, such as Fujian Road, wider streets allowed participants to gaze not only culturally significant buildings but also artificial structures such as fountains. In contrast, for traffic streets such as Sanming Road, narrower streets constrained participants' sightline, making street itself and vegetation the primary visual attractors. Additionally, a positive correlation was observed between building height and height-to-width ratio with storefront signage, particularly on commercially active streets such as Longtou Road. On these streets, the spatial disparity makes taller buildings and storefront signage more likely to attract visual attention.

3) Human scale: Sky openness was positively correlated with participants' visual attention to sky, while the volume of the field of view showed a positive correlation with traditional building, mountain/rocks, and fountain. For streets with higher sky openness, such as Fujian Road and Huangyan Road, traditional buildings and natural elements became visual attractors. These elements stood out due to their cultural and natural significance, forming a strong contrast with the surroundings, leading to frequent visual attention from participants. For example, in areas where Sunlight Rock is clearly visible, the unique natural landscape attracted significant visual attention. This finding confirms Gulangyu Island's identity as an "Architectural Museum of the World," which is represented not only in its diverse architectural styles but also in the harmonious integration of natural and built-up landscape elements, such as mountain/rocks and fountain. These elements may have been deliberately considered during the site selection of buildings, or carefully designed in different historical periods. Additionally, for streets with expansive field of view (e.g., Anhai Road), the sky that occupied a larger proportion but contained less detailed information tended to attract more visual attention.

4) Transparency: The proportion of wall was positively correlated with the visual attention to wall/railings. For narrower traffic streets, wall/railings, despite restricting participants' sightline, became prominent attractors due to their ornamentation and architectural details. The concept of transparency concerns how visual interfaces allow sightlines to penetrate, facilitating visual connection and interaction. In environments with limited visibility, where transparency is lacking, participants' attention is more likely to be drawn to decorative and detailed interfaces. The importance of transparency for spatial creation is also demonstrated by numerous international urban design practices. For example, in Alexandria, Egypt, specific ground-floor window ratio requirements have been implemented for commercial retail buildings, not only improving the visibility of activities on the street but also enhancing the vibrancy of the streetscape[48].

5) Complexity: The proportion of building was positively correlated with modern building but negatively correlated with street, vegetation, and sea. Similarly, color contrast gradient showed a positive correlation with modern building and a negative correlation with road sign. For streets where buildings occupied a higher proportion (such as residential streets), modern buildings became main visual attractors due to their vivid color contrasts. In contrast, for streets where road signs were the prominent visual attractors, muted or simple color schemes are often intentionally used to enhance the contrast gradient of these navigational elements, ensuring effective information conveying.

4.4 MNL Model Analysis of Visual Attractors and Physiological Indicators

To explore the relationship between psychological perception and physiological indicators, this study employed an MNL model to quantify the impact of different visual attractors on physiological responses. The results revealed that only 7 visual attractors—modern building, traditional building, street, wall/railings, sky, vegetation, and storefront signage—exhibited significant correlations with physiological indicators (Table 4).

Physiological responses were not particularly strong when participants fixated on modern buildings. However, fixation duration and HRV exhibited a significant negative correlation. Modern buildings are typically characterized by simplistic, structured, and smooth-lined facades, which lack organic elements and variation, compared with natural landscapes. This visual monotony may lead to reduced emotional arousal, consequently lowering HRV.

When participants fixated on traditional buildings, walls or railings, significant PD changes were observed in both eyes. Previous studies have found that pupil size is generally larger when viewing objects within the area of interest, compared with those outside the area[17]. Larger PD might relate to greater visual

Table 4: MNL model of the impact of eye-tracking selection behaviors on physiological data

Variable	Modern building		Traditional building		Road		Wall/ railings		Sky		Vegetation		Storefront signage	
	β	*SE*	*β*	*SE*	*β*	*SE*	*β*	*SE*	*β*	*SE*	*β*	*SE*	*β*	*SE*
FPOGD	0.011	0.031	−0.110	0.074	0.043	0.027	0.008	0.026	−0.450***	0.053	−0.071*	0.031	0.064	0.038
LPD	−0.119	0.066	0.363*	0.146	0.110	0.058	−0.205***	0.056	0.087	0.092	−0.047	0.065	0.155	0.084
RPD	0.116	0.066	−0.294*	0.143	−0.112	0.057	0.214***	0.055	−0.174	0.090	−0.022	0.064	−0.240**	0.082
GSR	0.008	0.030	0.015	0.068	0.075**	0.026	−0.025	0.026	−0.185**	0.059	−0.029	0.031	0.084*	0.034
HR	−0.052	0.030	0.100	0.070	0.131***	0.027	0.023	0.025	−0.186***	0.045	−0.043	0.030	−0.034	0.039
HRP	−0.089**	0.033	−0.157	0.082	−0.013	0.027	0.050*	0.025	0.003	0.047	−0.046	0.032	0.105**	0.035
Constant (c)	−1.311***	0.030	−3.419***	0.071	−0.749***	0.026	−0.443***	0.025	−2.529***	0.049	−1.303***	0.030	−2.028***	0.038
LR $chi^2(6)$	15.470		13.270		35.970		23.410		118.730		18.720		23.940	
Prob > chi^2	0.017		0.039		0.000		0.001		0.000		0.005		0.001	
Log likelihood	−3,484.395		−962.746		−4,220.049		−4,502.262		−1,846.143		−3,495.798		−2,429.947	
Pseudo R^2	0.002		0.007		0.004		0.003		0.031		0.003		0.005	

NOTES

1. * indicates $p < 0.05$, ** indicates $p < 0.01$, and *** indicates $p < 0.001$.
2. Other visual attractors that did not exhibit significant regression coefficients are not listed.

interest in traditional buildings, walls or railings, while smaller PD could be associated with recalled memories and cognitive load[49]. That is, visitors may need to consume more attention to process and retrieve memories related to traditional architecture.

Street exhibited a significant positive correlation with GSR and HR. This may be because visual stimuli on the street (e.g., pavement patterns, directional signs) captured participants' attention, and led to increased GSR and HR.

Wall/railings showed a significant positive correlation with HRV, meaning that higher and denser wall/railings were associated with greater HRV values. This can be explained by the frame effect created by tall and dense barriers, where lower street transparency induced feelings of oppression and discomfort, thereby increasing HRV.

Sky and vegetation exhibited a significant negative correlation with fixation duration. Previous research has confirmed that although sky and greenery often occupy a large portion in the field of view, they contain relatively low information density, leading to shorter fixation durations[50][51]. Additionally, sky, as an open and calming element, had a significant negative impact on GSR and HR, meaning that observing the sky led to decreases in both physiological indicators.

When participants fixated on storefront signage, smaller RPD, a slight increase in GSR, and a significant increase in HRV were observed. This can be explained by the increased cognitive load required participants to examine the signage in-detail, which induced smaller PD[49]; while storefront signage stimulated participant interest, leading to increases in both GSR and HRV.

4.5 Regression Analysis of Psychological Perception and Physiological Indicators

Through a preliminary regression analysis of psychological perception and physiological indicators with OLS models, the study found that only fixation duration, PD, and HR exhibited statistically significant correlations with the psychological perception items (enclosed–open, lively–quiet, and dark–bright)

(Fig. 9). The R^2 values for these models were 0.14, 0.12, and 0.11, respectively, indicating that Model 1 explained 14% of the variance in fixation duration, Model 2 explained 12% of the variance in RPD, and Model 3 explained 11% of the variance in HR.

In terms of street openness, Model 1 indicated a positive correlation between fixation duration and perceived openness, suggesting that spacious streetscapes led to longer visual fixations. This implies that wide, open spaces may enhance attention and induce pleasant feelings, aligning with the finding by Shanzhi Kang et al., which demonstrated that open spaces contribute to positive emotional experiences[14].

Regarding street vitality, Model 2 showed that stronger perception of bustling streetscape (indicating the presence of more areas of visual interests on the street) corresponded to larger PD. Previous studies have also confirmed that outdoor signage in the streets enhances visitors' attention[50], which in turn leads to larger PD.

In terms of lighting, Model 3 revealed that greater perception of brightness was associated with lower HR, suggesting that well-lit streetscapes promote positive emotions, making the participants more relaxed and calm.

5 Discussion

5.1 Analysis of the Physical–Physiological–Psychological Interaction Mechanisms

Examining participants' spatial perception in historical streets and its influencing factors and based on the above experiment results, this study further summarized the physical–physiological–psychological interaction mechanisms underlying as follows.

1) Physical factors, particularly architectural style, layout of commercial spaces, spatial scale, and interface transparency, directly influence visitors' visual experience and preferences.

2) Physiological indicators, such as fixation duration, HR, and PD variations, reflect visitors' real-time emotional responses to different visual attractors in the streets, revealing the potential of local distinctiveness of historical streets in enhancing tourism experiences.

3) Psychological factors serve as a bridge between the physical environment and physiological responses. The correlation analysis between psychological perception and physiological indicators confirmed the "physical environment–eye-tracking fixation–emotional arousal" mechanism of visitors' visual preferences, highlighting that street openness, vitality, and lighting are key factors in enhancing pedestrian experience.

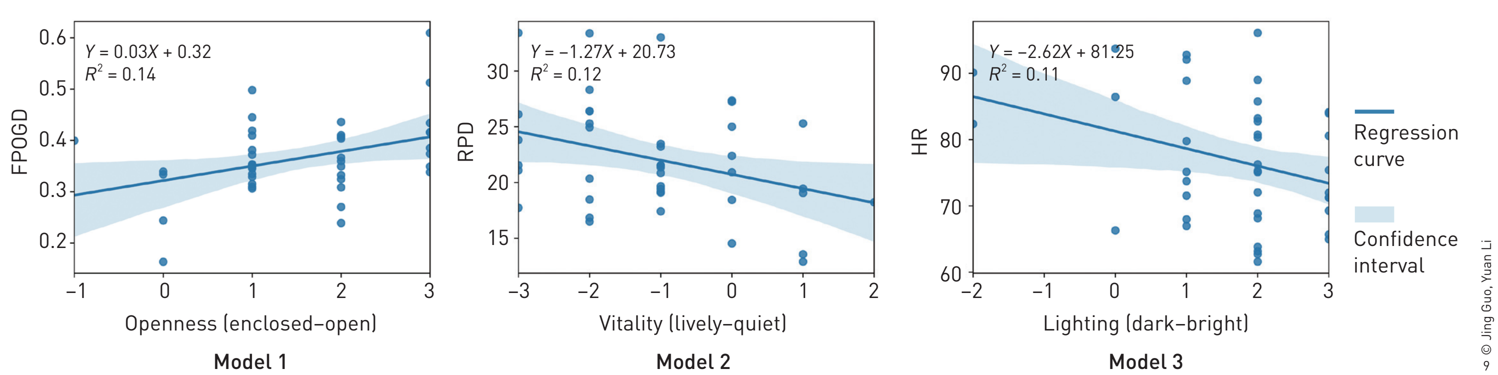
5.2 Optimization Strategies for Historical Streets

1) Traffic streets. These streets are characterized by numerous walls and facades, abundant greenery, but a visually monotonous spatial experience. To improve visual appeal, it is necessary to increase street width and openness while enhancing wall transparency. For instance, installing interactive facilities and display installations while maintaining traffic efficiency can enhance street vitality.

2) Residential streets. These streets are often narrow, with low openness, dense modern buildings, and limited natural elements. Considering the needs of both local residents and visitors, facade renovation can be implemented to improve street cleanliness and openness. This can be achieved through strategies such as creating small-size green spaces (e.g., pocket parks), integrating the residential streets with the natural environment.

3) Commercial–residential streets. As places attracting visitors' attention, these streets feature varied storefront signage and lighting interplay. Optimization measures include enhancing lighting control to prevent physiological discomfort caused by dramatic lighting fluctuations of signage; and improving business management for a better integration of modern commerce and historical buildings.

4) Mixed-use streets. Such streets densely accommodate cultural



9. Regression analyses of psychological perception and physiological sensing data.

architectural heritages. However, due to heritage protection requirements, they often have massive walls and facades with low transparency and weak interaction. To enhance visual appeal while preserving historical structures, measures of increasing the transparency of street interfaces can be taken. For example, by leveraging VR and AR technologies to reconstruct historical scenes and buildings, or to introduce digital heritage exhibitions and NPC-guided interactions, visitors' attention and engagement would be enhanced.

6 Conclusions

This study employed an eye-tracking and physiological sensing experiment to explore participants' spatial perception in historical streets and related influencing factors, capture individual visual attention preferences, and uncovered the physical–physiological–psychological interaction mechanisms underlying participants' spatial perception in historical streets. The findings indicate that, at the physical level, architectural and commercial elements in historical streets significantly influence visitors' spatial perception. Specifically, streetscapes characterized by high imageability, low enclosure, high openness, high transparency, and high complexity attract greater visual attention and elicit stronger emotional responses. At the physiological level, HR and PD reveal visitors' visual preferences for different street types. In traffic streets, walls and railings were the dominant visual attractors; in commercial–residential streets, storefront signage was the primary visual attractor; in residential streets, modern buildings attracted more attention; and in mixed-use streets, participants exhibited a preference for traditional buildings, particularly architectural heritage components and natural elements. At the psychological level, the perceived street openness, vitality, and lighting influenced participants' physiological responses, demonstrating that the visual appeal and emotional arousal of the environment significantly affect individuals' visual preferences.

The physical–physiological–psychological research framework for spatial perception proposed in this study enriches the application of environmental psychology theories in historical street research and offers a novel perspective for studies on pedestrian-friendly historical streets. Methodologically, this study developed a 3D virtual geographic environment and an integrated eye-tracking and physiological sensing experiment, providing a new quantitative approach to exploring environmental perception in historical streets and improving the precision of research results. In terms of application, the study offers human-centered urban renewal strategies for the four types of historical streets in Gulangyu Island.

Despite its contributions, this study has some limitations. Future research should further assess the fidelity of the 3D virtual geographic environment and enhance experimental fluidity, such as adopting head-mounted VR eye-tracking systems. More historical streets should be studied with the research framework proposed in this paper, and deep learning techniques can be utilized to enhance the accuracy and efficiency of data analysis, refining optimization strategies for historical streets.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to the Xiamen Urban Planning Digital Technology Research Center and the Xiamen Gulangyu–Wanshi Mountain Scenic Area Administration Committee for providing the foundational 3D model data and reference materials for the research. Sincere appreciation is also extended to the anonymous peer reviewers for their thorough review and valuable insights.

Competing interests | The authors declare that they have no competing interests.

REFERENCES

[1] Wu, Y., Dong, W., & Zhang, W. (2022). Research on influencing factors of built environment perception in neighborhoods: Evidence from behavioral experiment. *City Planning Review*, 46(12), 99–109.

[2] Zhang, Z., Xu, G., Li, W., Long, Y., & Cao, Z. (2019). The impact of the micro-scale built environment of historic street on visitor's walking behaviors: A case study on Wudaoying Hutong in Beijing. *Architectural Journal*, (3), 96–102.

[3] Wu, Z., Zhang, L., Zheng, Z., Zhang, B., & Liao, Z. (2019). The production of space within the field of tourism: A case study of the tourism community of Chaozhou ancient city. *Tourism Tribune*, 34(12), 86–97.

[4] Liu, J., Zhang, M., Zhang, X., & Hong, X. (2023). Relationship between soundscape and place attachment of tourists in historic block: A case study of Jinli Ancient Street. *Chinese Landscape Architecture*, 39(1), 59–64.

[5] Shi, C., Yuan, Q., Pan, H., & Ye, Y. (2020). Measuring walkability of street space and its design control in the context of new analytical techniques: A case study of Shanghai Jing'an Temple area. *Shanghai Urban Planning Review*, (5), 71–79.

[6] Li, Y., Huang, J., Liang, J., Zhang, Y., & Chen, Y. (2022). Research on visual attraction and influencing factors of perception of commercial street space in cultural heritage site: Taking Gulangyu Longtou Road as an example. *Journal of Human Settlements in West China*, 37(2), 114–121.

[7] Marques, L. F., Tenedório, J. A., Burns, M., Romão, T., Birra, F., Marques, J., & Pires, A. (2017). Cultural heritage 3D modelling and visualisation within an augmented reality environment, based on geographic information technologies and mobile platforms. *ACE: Architecture, City and Environment*, 11(33), 117–136.

[8] Ma, Y. (2021). Extending 3D-GIS district models and BIM-based building models into computer gaming environment for better workflow of cultural heritage conservation. *Applied Sciences*, 11(5), 2101.

[9] Tang, J., & Long, Y. (2019). Measuring visual quality of street space and its temporal variation: Methodology and its application in the Hutong area in Beijing. *Landscape and Urban Planning*, (191), 103436.

[10] Li, B. (2008). Environmental behavior theory in environmental behavior studies and its expansion. *Architectural Journal*, (2), 30–33.

[11] Zhuang, C., & Zhang, J. (2011). Place identity: Analysis from environmental psychology perspective. *Advances in Psychological Science*, 19(9), 1387–1396.

[12] Chen, Y., Chen, Z., & Du, M. (2022). Designing attention—Research on landscape experience through eye tracking in Nanjing Road Pedestrian Mall (Street) in Shanghai. *Landscape Architecture Frontiers*, 10(2), 52–70.

[13] Zhang, Z., & Long, Y. (2019). Application of wearable cameras in studying individual behaviors in built environments. *Landscape Architecture Frontiers*, 7(2), 22–37.

[14] Kang, S., Chen, X., Huang, C., Li, J., Yan, J., & Ye, Y. (2023). The exploration of street micro-renewal technology from the perspective of new urban science: A case study of Guzong Road in Nanhui New City. *New Architecture*, (6), 52–57.

[15] Chen, B., Gong, C., & Li, S. (2022). Looking at buildings or trees? Association of human nature relatedness with eye movements in outdoor space. *Journal of Environmental Psychology*, (80), 101756.

[16] Zhang, R., Li, G., Zhang, L., & Huang, Q. (2023). Research on visual perception of historical district's cityscape by VR eye-tracking technology: A case study of Zhangzhou Ancient City. *New Architecture*, (6), 58–63.

[17] Liu, L., Wu, M., Ma, Y., & Qu, H. (2021). A review of eye tracking researches in landscape architecture field. *Journal of Human Settlements in West China*, 36(4), 125–133.

[18] Chen, Z., & Liu, S. (2018). Real-time environmental affective experience assessment via wearable sensors. *Chinese Landscape Architecture*, 34(3), 12–17.

[19] Ye, Y., & Dai, X. (2017). Spatial perception and design potentials in the context of new analytical techniques and new data. *Time+Architecture*, (5), 6–13.

[20] Ewing, R., Handy, S., & Jiang, W. (2012). Measuring the unmeasurable: Urban design qualities related to walkability. *Urban Planning International*, 27(5), 43–53.

[21] Ewing, R., & Handy, S. (2009). Measuring the unmeasurable: Urban design qualities related to walkability. *Journal of Urban Design*, 14(1), 65–84.

[22] Ren, X. (2019). Consensus in factors affecting landscape preference: A case study based on a cross-cultural comparison. *Journal of Environmental Management*, (252), 109622.

[23] Hollander, J. B., Sussman, A., Purdy Levering, A., & Foster-Karim, C. (2020). Using eye-tracking to understand human responses to traditional neighborhood designs. *Planning Practice & Research*, 35(5), 485–509.

[24] Noland, R. B., Weiner, M. D., Gao, D., Cook, M. P., & Nelessen, A. (2017). Eye-tracking technology, visual preference surveys, and urban design: preliminary evidence of an effective methodology. *Journal of Urbanism: International Research on Placemaking and Urban Sustainability*, 10(1), 98–110.

[25] Shemesh, A., Leisman, G., Bar, M., & Grobman, Y. J. (2022). The emotional influence of different geometries in virtual spaces: A neurocognitive examination. *Journal of Environmental Psychology*, (81), 101802.

[26] Lin, H., Hu, M., Chen, M., Zhang, F., You, L., & Chen, Y. (2020). Cognitive transformation from geographic information system to virtual geographic environments. *Journal of Geo-Information Science*, 22(4), 662–672.

[27] Liu, H., & Xue, M. (2021). Exploring the use of virtual geographic environments for geo-spatial cognition research. *National Remote Sensing Bulletin*, 25(10), 2027–2039.

[28] Shao, Y., Ye, D., & Ye, Y. (2023). Measuring the transparency of street interface based on street view images and deep learning: Taking Shanghai as an example. *Urban Planning International*, 38(6), 39–47.

[29] Li, X., Shang, W., Liu, Q., Liu, X., Lyu, Z., & Ochieng, W. (2024). Towards a sustainable city: Deciphering the determinants of restorative park and spatial patterns. *Sustainable Cities and Society*, (104), 105292.

[30] Ye, Y. (2019). The new potentials of urban design in the context of new urban science. *Journal of Human Settlements in West China*, 34(1), 13–21.
[31] Xu, L., Meng, R., Huang, S., & Chen, Z. (2019). Healing oriented street design: Experimental explorations via virtual reality. *Urban Planning International*, 34(1), 38–45.
[32] Li, Y., & Guo, J. (2023). Research on heritage value perception of historical streetscapes based on 3D virtual geographic environment under the background of digital cultural tourism: Taking Gulangyu Island in Xiamen as an example. *China Ancient City*, 37(6), 50–59.
[33] Wu, Z., & Ai, X. (2020). Research of spatial visual features of Quanzhou Dacuo houses based on 3D GIS. *Journal of Huaqiao University (Philosophy & Social Sciences)*, (2), 140–150.
[34] Wu, C., Zhou, S., & Ye, Y. (2021). The application of human behaviour modelling in urban ergonomics design. *World Architecture*, (3), 46–49, 126.
[35] Xiamen Municipal People's Government. (2020). *Gulangyu Historic and Cultural District Conservation Plan*.
[36] Li, Y., Guo, J., & Chen, Y. (2022). A new approach for tourists' visual behavior patterns and perception evaluation based on multi-source data. *Journal of Geo-Information Science*, 24(10), 2004–2020.
[37] Huang, J., Liang, J., Yang, M., & Li, Y. (2024). Street space visual quality evaluating method of tourism sites based on street view images. *Journal of Geo-Information Science*, 26(2), 352–366.
[38] Pei, W., Guo, X., & Lo, T. (2021). Biofeedback in the dynamic VR environments: A method to evaluate the influence of architectural elements on human spatial perception. *WABD 2021: 2021 Workshop on Algorithm and Big Data*.
[39] Yao, Y., Liang Z., Yuan, Z., Liu, P., Bie, Y., Zhang, J., Wang, R., Wang, J., & Guan, Q. (2019). A human-machine adversarial scoring framework for urban perception assessment using street-view images. *International Journal of Geographical Information Science*, 33(12), 2363–2384.
[40] Ge, Y., Chen, Y., Liu, Y., Li, W., & Sun, X. (2014). Electrophysiological measures applied in user experience studies. *Advances in Psychological Science*, 22(6), 959–967.
[41] Li, Y., Yang, L., & Gao, X. (2019). Preference and spatial improvement strategies of street space of Gulangyu Island. *Planners*, 35(14), 24–31.
[42] García-Palomares, J. C., Gutiérrez, J., & Mínguez, C. (2015). Identification of tourist hot spots based on social networks: A comparative analysis of European metropolises using photo-sharing services and GIS. *Applied Geography*, (63), 408–417.
[43] Ord, J. K., & Getis, A. (1995). Local spatial autocorrelation statistics: Distributional issues and an application. *Geographical Analysis*, 27(4), 286–306.
[44] Ye, Y., Zhou, X., & Wang, Z. (2019). A quantitative approach for measuring positive social impacts of tall buildings' lower public space: Utilizing virtual reality and biosensors techniques. *Time+Architecture*, (6), 152–159.
[45] Wang, C., Wang, D., Zhu, W., & Song, S. (2015). Research progress of discrete choice models. *Progress in Geography*, 34(10), 1275–1287.
[46] Zhang, R., & Yin, B. (2020). Research on the influence of environmental perception of guiding path preference under spatial value matching: A case study of Gulangyu. *World Architecture*, (11), 115–119.
[47] Wang, J., & Chen, Z. (2020). Study on the change of gate building style in modern Gulangyu. *Architecture & Culture*, (6), 134–137.
[48] Li, X., Li, Y., Ren, Y., & Lask, A. (2020). Research on the urban spatial visual quality based on subjective evaluation method and eye tracking analysis. *Architectural Journal*, (S2), 190–196.
[49] Kucewicz, M. T., Dolezal, J., Kremen, V., Berry, B. M., Miller, L. R., Magee, A. L., Fabian, V., & Worrell, G. A. (2018). Pupil size reflects successful encoding and recall of memory in humans. *Scientific Reports*, (8), 1–7.
[50] Chen, Z. (2023). Positive nudges for urban regeneration via eye-tracking and behavioural evidence. *World Architecture*, (7), 68–69.
[51] Jin, Y., Kuang, X., Xi, T., & Chen, Z. (2023). Accurate transformation of street greening promoted by decision-making on health behavior. *Landscape Architecture*, 30(1), 45–53.

https://doi.org/10.15302/J-LAF-0-020029 收稿日期 | 2024-01-02 录用日期 | 2024-09-24 中图分类号 | TU985 文献标识码 | A

基于眼动和生理传感数据的虚拟历史街道空间感知研究

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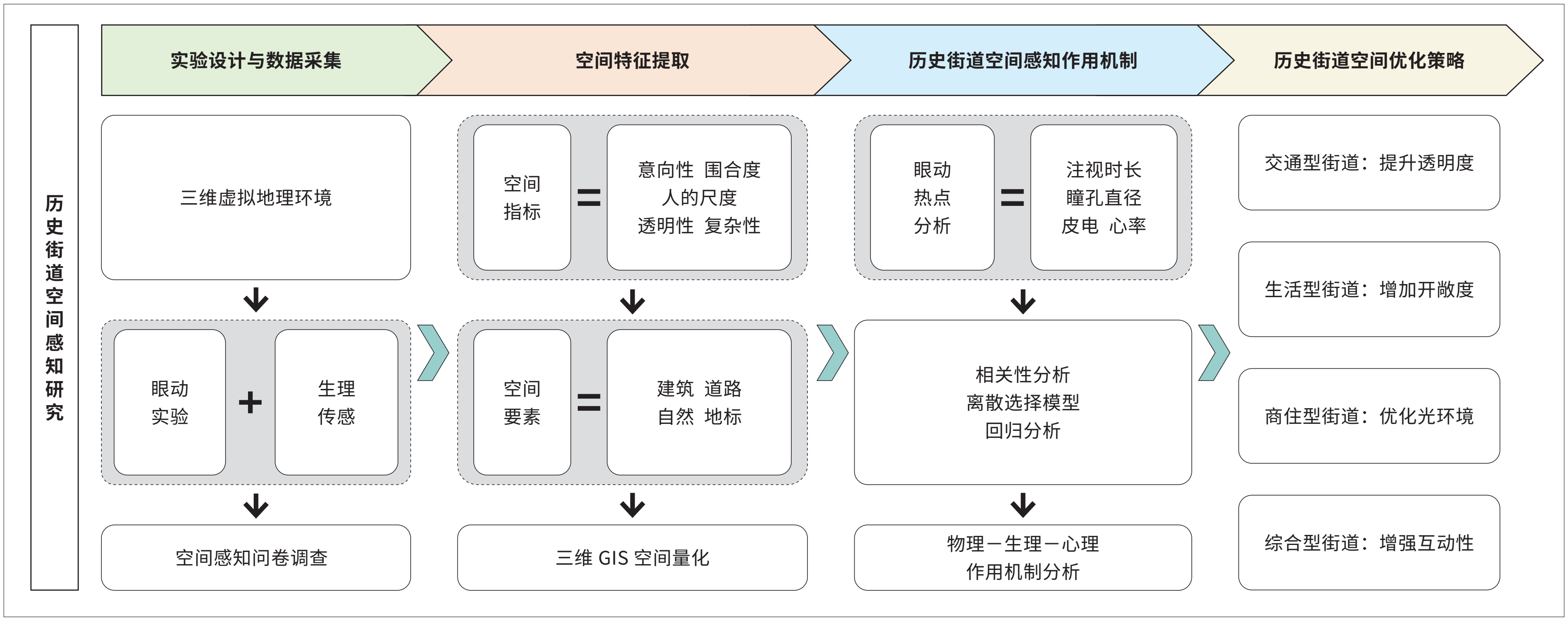
图文摘要



摘要

历史街道是城市形态的重要组成部分和城市文化的物质载体，精细量化分析游客在历史街道中的空间感知是提升街道空间品质的重要基础。本研究以厦门市鼓浪屿为例，通过构建三维虚拟地理环境，提出“物理－生理－心理”空间感知研究路径：基于环境行为学理论和街道设计质量的5个维度评估历史街道的物理空间特征、游客眼动和生理传感数据，以及心理感知，总结历史街道环境对游客心理感知的作用机理，并提出相应的街道空间优化方案。研究发现：1）历史街道的物理空间特征，包括建筑风格、商业布局、空间尺度及界面透明度，直接影响游客的视觉体验和视觉选择决策；2）视觉关注与街道空间的意象性、开敞度、透明性及复杂度之间显著正相关，与围合度之间显著负相关，其中街道宽敞度、活力和光线是主要影响游客生理反应的因素；3）“物理－生理－心理”作用机制表明，街道环境的视觉吸引力和情绪激发能显著影响个体的感知和行为决策，证实了视觉选择行为背后的“物理环境－眼动注视－情绪激发”过程。最后，研究针对不同街道类型提出空间感知优化策略，以为历史街道更新提供决策参考。

关键词

三维虚拟地理环境；历史街道；空间感知；“物理－生理－心理”空间感知研究路径；环境行为学；鼓浪屿

文章亮点

- 提出一种基于三维虚拟地理环境的历史街道空间感知研究方法，构建了“物理－生理－心理”研究路径
- 街区的建筑风格、商业布局和空间开敞度显著影响游客的视觉关注与情绪反应
- 总结了游客在历史街道中的“物理－生理－心理”作用机制

基金项目

国家自然科学基金面上项目“遗产价值视角下的旅游者空间感知评价与优化研究”（编号：42171219）

编辑 田乐，王胤瑜

1 引言

随着中国城镇化进程的推进，城市规划已从传统的规模扩张转向质量提升[1]。历史街道的建成环境不仅是影响游客步行行为的重要因素[2]，也是传递地方历史记忆和文化特征的关键载体，对遗产保护和旅游发展具有重要意义。然而，历史街道也面临着使用功能转变的挑战[3]，这不仅会改变街道的物理环境，也会深刻影响游客的地方认同感[4]。因此，研究游客在历史街道中的空间感知及相关影响因素，对于历史街道有机更新、提升旅游体验具有重要的理论和实践意义。

2 文献综述

历史街道作为重要的文化遗产受到学界广泛关注。有学者通过虚拟现实、眼动追踪、语义差异法等方法，探讨了历史街道的步行适宜性和视觉吸引力。例如，施澄等人基于虚拟现实和决策树算法对步行适宜性的精确测度，为城市街区微更新提供了实践参考[5]；张章等人通过实地调研，揭示了建筑尺度、立面构成特征与游客步行停驻行为之间的关系，提出了历史街道设计的优化建议[2]；李渊等人运用眼动实验，解析了商业历史街道的视觉吸引力与游客感知的复杂关系[6]。也有学者利用三维虚拟地理环境与GIS技术对历史街道进行展示与管理。例如，路易斯·马克斯等人提出基于移动平台和增强现实技术的文化遗产3D建模和可视化方法[7]；马玉萍利用BIM和3D建模技术改进了文化遗产的保护流程[8]；唐静娴等人利用腾讯街景图片，结合SegNet机器学习与2D、3D分析，评估北京胡同的绿化、开放性、围合度等视觉质量[9]。总体而言，国内外围绕历史街道的物理环境重现展开研究，通过虚拟现实、眼动实验等方法探索人本尺度的空间感知和行为模式，为未来深化历史街道的保护与优化设计提供了技术和理论基础。

环境心理学理论关注人和环境的关系，特别是环境因素对个体心理影响的作用机制[10][11]。近年来，眼动追踪[12]、穿戴式相机[13]、生理传感[14]和虚拟现实[15]等新技术的涌现，使环境心理学者可以更精确和更直观地分析人们在街道中的视觉关注[16]、空间感知[17]和实时环境情绪感受[18]，为“人本视角”的街道更新设计提供了强有力的支持[19]。

在空间感知的相关研究中，已有学者从多个层面探讨了街道空间的感知测度。在物理层面上，里德·尤因和苏珊·汉迪通过专家评分方法测度了城市街道设计质量，并提出了由意象性、围合度、人的尺度、透明性和复杂性5个维度构成的评估框架[20][21]，这一框架被广泛认为是评估和提升城市街道设计品质的关键要素。在生理层面上，陈筝等人结合时空轨迹和生理情绪数据，有效映射了受试者对空间的情绪反应[18]，为环境设计领域提供了新的视角。从心理层面出发，眼动追踪技术已被广泛应用于研究旅游者的景观偏好[22]、对街道建筑等环境元素的主观偏好等[23]~[25]。

随着三维虚拟地理环境[26][27]、机器学习[28][29]、多源大数据[30]等技术的发展，研究人员能够更便利地构建虚拟实验场景[31]，并进行眼动关注要素的语义分割[6]。这些进步不仅克服了以往研究中街道空间感知实验结果易受行人因素干扰的限制[14][23]，且有助于创建成本较低、条件可控的三维虚拟地理环境[32]，还可有效刻画历史街道的细部特征和微观环境[33]，实现对人行为的建模[34]和数据的融合分析。

综上所述，尽管现有的街道感知评估方法及新兴数据和技术的运用已为历史街道空间感知的评估提供了重要借鉴，但尚缺乏在虚拟历史街道场景中结合眼动追踪和生理传感的研究。本研究依托环境行为学理论和街道设计质量5个维度，提出一种基于虚拟地理环境的历史街道空间感知研究路径，并创新性地将眼动追踪技术与虚拟现实相结合，以精确捕捉游客的视觉关注点。研究旨在探索游客在历史街道中的空间感知，进而为历史街道空间优化提供针对性建议。

3 研究方法

3.1 研究路径框架

研究提出“物理—生理—心理”历史街道空间感知研究路径。首先，在物理层面，通过计算历史街道环境特征及空间属性，选取了5个评价指标——意象性、围合度、人的尺度、透明性和复杂度——来量化街道空间特征；其次，在生理层面，通过在虚拟地理环境中进行眼动和生理传感实验，采集注视时长、瞳孔直径、皮电、心率、心率变异性等生理指标，分析不同空间因素对感知的影响；最后，在心理层面，通过实验后评价来进一步分析受试者对不同空间要素的具体感知反馈，提出历史街道空间的优化建议（图1）。

3.2 研究区域

鼓浪屿是一座位于厦门岛西南隅、面积约1.88km^{2}的小岛，岛内道路系统主要由35条历史道路组成，街道历史风貌显著，游人以步行体验为主[35]。综合《鼓浪屿历史文化街区保护规划》[35]、前期实地调研结果及相关既有研究[36][37]，选择了一条最大化串联鼓浪屿核心遗产建筑要素，并包含交通型、商住型、生活型和综合型四种类型街道的研究路线（表1，图2），路线总长度约3.5km，正常步行速度下虚拟漫游时长为20～30分钟。

3.3 实验受试者

通过网络和线下招募，共有41名厦门大学学生参与本研究的眼动和生理传感实验，其中女性占73.2%，男性占26.8%①。实验于2022年11月22～29日在厦门建筑遗产保护智能技术应用综合重点实验室进行。92.7%的受试者有鼓浪屿到访经历，方差分析结果显示，是否去过鼓浪屿对评价结果无显著影响。在对虚拟场景真实性还原度的评价调查中，受试者平均评分为4.09（满分5），即虚拟地理环境能较大程度还原鼓浪屿历史街道的真实游览体验（图3，4）。为了排除游人因素对受试者目光分配和心理感知的干扰，以便让受试者聚焦于物理环境本身的影响，实验所用的虚拟场景中未包含游客画面。

表 1：鼓浪屿历史街道类型及特征

街道类型	特征
交通型	主要为连接功能，多位于建筑山墙或围墙之间，呈狭窄的线形空间
商住型	位于较为集中的商业区，在商业区中形成了底层商业、二层以上居住的街道
生活型	由线形分布于两侧的居住单元组合而成
综合型	呈现出多种功能（商业、居住）糅杂的形态，包括各类遗产建筑

3.4 数据采集与多源融合

实验采用Gazepoint GP3设备同步采集受试者的眼动和生理传感数据。

第一步，基于UE 4游戏引擎搭建三维虚拟地理环境[32]，受试者签署知情同意书和进行眼动校正后，在研究路线中进行虚拟漫游，并在结束后填写空间感知调查问卷。

第二步，参考以视频和虚拟漫游场景作为刺激材料的相关研究[1][14][38]，以10s为单位，对眼动和生理传感数据进行切片分析，记录空间坐标变化，同时标注对应的眼动热区和生理指标变化。

第三步，对实验路线进行分段处理，并利用SuperMap软件的三维GIS分析功能对历史街区的物理环境进行详细分析。此外，采用ADE20K数据集进行每段街道视野范围的机器学习要素语义分割。该数据集包含逾27 000张经过精细注释的图像，在场景理解领域获得了学术界的广泛认可[29][39]。

第四步，基于第二步的切片数据，对生理传感数据进行进一步统计，以每10s为一个时间窗口，对窗口内的数据进行平均值计算，以平滑极端值所带来的波动，确保分析结果的准确性和可靠性。

第五步，将上述各项数据基于统一的空间坐标集成于GIS平台，共获得8 375个空间坐标点及其对应的眼动和生理传感数据、每段街道的空间指标数据层，以及受访者的感知问卷数据。

3.5 指标选择与测量

3.5.1 物理层面指标

综合前人的研究[2][20][32][38]、鼓浪屿的历史街道空间特征和计算可操作性，研究基于意象性、围合度、人的尺度、透明性和复杂度5个街道设计质量维度，选取了15个历史街道空间要素描述指标（表2）。

3.5.2 生理层面指标

参考既有研究[18][22][38][40]，本研究选择以下生理层面指标来识别受试者对历史街道空间要素的注意力分布和情绪刺激反应。

1）注视点持续时间：指观看感兴趣的对象时的注视点持续时间（通常以ms为单位），可反映人眼对环境中感兴趣的物体的注意力分配情况。

① 多数眼动实验邀请30名左右受试者参与实验，仅少数研究达到60名（如参考文献[17]），故认为本研究样本数量达到此类研究的合理水平。

表 2：历史街道空间特征指标

维度	空间特征指标	释义	计算方式
意象性	人群活跃度	街道公共空间中人们的活动程度	百度地图热力图统计
	历史建筑占比	所有建筑中历史建筑的占比（本研究将建造于 20 世纪初及之前的建筑定义为历史建筑）	建筑年代统计
围合度	街道宽度	街道的宽度	三维 GIS 量算
	街道高度（同侧）	街道同侧建筑的高度	三维 GIS 量算
	街道高度（对侧）	街道对面建筑的高度	三维 GIS 量算
	街道高宽比（同侧）	同侧建筑高度和街道宽度的比值	三维 GIS 量算
	街道高宽比（对侧）	对面建筑高度和街道宽度的比值	三维 GIS 量算
	天空占比	可见天空面积占可视域的比例	场景截图语义分割
人的尺度	天空开敞度	头顶天空的开敞程度	三维 GIS 开敞度分析
	长视线	最长可视距离	三维 GIS 视线分析
	可视域体积	可视域范围内的立体空间大小	三维 GIS 可视域分析
	可视域面积	可视域范围内的平面面积大小	三维 GIS 可视域分析
透明性	墙壁占比	可视域范围内的墙壁占比	场景截图语义分割
复杂性	建筑占比	可视域范围内的建筑占比	场景截图语义分割
	环境色彩对比度	建筑及周围环境的色彩对比度	RGB 平均值

注

1. 在虚拟漫游过程中，受试者前进方向的右侧称为“同侧”，左侧称为“对侧”。
2. “立体空间”和“平面面积”是基于三维 GIS 分析的空间几何概念：前者指场景中观察者可视域范围内空间的三维体积，其范围由地面（包括建筑基底）、建筑墙体和屋顶等边界所围合；后者指观察者可视域范围内沿水平视平面投影后的二维面积，主要反映观察者视线投射到地面后的空间覆盖情况。

2）瞳孔直径：瞳孔直径大小受人的视神经系统控制，可反映视觉兴奋程度。

3）皮电：指人体皮肤对外界刺激的电性反应，在情绪研究中，GSR常被用于测量情绪激动程度。

4）心率和心率变异性：心率是指单位时间内心脏跳动的次数，心率变异性是指心率在不同时间点之间的变化程度，这两个指标常被用于测量情绪激发程度。

3.5.3 心理层面指标

基于前人的研究[41]，本研究采用调查问卷的方式来获取街道空间体验的心理感知数据。问卷采用心理学研究中的语义差异法，提供11对形容词来描述街道空间特征，要求受试者对每个感知项进行评价，分别赋值–3～3，0表示感知程度一般，–1和1表示感知程度适中，–2和2表示感知程度较强，–3和3表示感知程度非常强（图5）。

3.6 统计方法与模型

3.6.1 空间热点分析

本研究采用Getis-Ord G_i^*方法来分析眼动关注要素和生理传感数据是否存在显著的空间集聚。Getis-Ord G_i^*是一种常见的空间热点分析方法[42]，它计算每个要素周围其他要素的值，并根据这些值确定每个要素

的统计显著性，以评估空间集聚的强度和位置。其计算公式如下[43]：

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \overline{X} \sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{\left[n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}}, \quad (1)$$

$$\overline{X} = \frac{\sum_{j=1}^{n} x_j}{n}, \quad (2)$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j}{n}}, \quad (3)$$

其中，x_j是j要素的属性值，$w_{i,j}$是要素i和j之间的空间权重，n为要素总数。G_i^*统计的结果为z得分，对于具有显著统计学意义的正z得分，分值越高，表示高值（热点）的聚类越密集；对于显著性负z得分，分值越低，表示低值（冷点）的聚类越密集。

3.6.2 离散选择模型

本研究认为，影响受试者视觉关注选择的时空因素十分复杂，因此采用离散选择模型来分析受试者的生理反馈对视觉选择行为的影响。根据现有文献[44]和数据可用性，受试者空间视觉偏好选择行为多元胜算对数（MNL）模型表达式如下[45]：

$$P(y=i) = \frac{e^{\beta x}}{\sum e^{\beta x}}, \quad (4)$$

式中，被解释变量y是受试者对视觉要素i的选择行为，根据眼动热力区统计输出为两类互斥的类型（选择或不选择），对应取值为1或0。在多项回归分析中，解释变量x为受试者的生理传感数据，数据经过标准化处理；β为解释变量系数。

4 研究结果

4.1 空间热点分析

分析结果（图6）显示，受试者在游览龙头路、安海路等商住型街道时，注视点持续时间显著增长，反映出这些街道独具特色的商业风貌和高信息密度的环境要素（如商店招牌和出入口空间）吸引了受试者持久的视觉关注。相比之下，福建路、三明路和永春路等综合型街道由于历史风貌独特及空间要素的信息密度（如遗产建筑、院落和地标）相对丰富，致使受试者的视线更频繁地转移，注视点持续时间显著缩短。

在安海路、福建路等生活型和综合型街道，瞳孔直径的显著增大与这些街道上的核心印象类空间要素（如新老建筑交融）紧密相关，为受试者提供了丰富的视觉刺激和深刻的情感联结。而在绿化环绕的笔山路、鼓新路等交通型街道，较暗的环境光线和底层灌木会吸引视线集中，导致受试者瞳孔直径呈现高值集聚。

在中华路、市场路和龙头路等商住型街道，受试者的皮肤电反应强度显著提高。这类街道不仅包括多样化的沿街商店和高密度的建筑布局，还包括较强的街道照明和良好的视线通达性，这些因素共同形成了更加丰富的视觉体验。陈筝等人在关于上海南京路的眼动研究中也揭示了户外店招如何塑造街道上“独特”“丰富”和“鲜明”的景观风貌，为行人带来深刻的视觉印象[12]。

心率及心率变异性的高值区域集中于鹿礁路和福建路附近，这些路段的核心遗产建筑不仅吸引了受试者的浓厚兴趣，更强化了与其个人记忆和过往经历紧密相连的情感纽带。例如，一些受试者口述，在漫游福建路时，会回忆起他们之前参观过“海天堂构”建筑群的经历。

4.2 视觉吸引物空间热点分析

根据相关文献[46]和鼓浪屿历史街道空间特征，本研究将眼动选择偏好的视觉吸引物分为四类：建筑要素、道路要素、自然要素和地标要素，共16项。其中，建筑要素依据其建造年代和样式不同[47]，分成现代建筑、传统建筑、西式建筑和遗产构件4个子项（表3）；道路要素包括道路、广场、阶梯／陡坡、围墙／栏杆4个子项；自然要素包括天空、植物、山体／岩石、海4个子项；地标要素包括商店招牌、喷泉、路灯、路标／地名4个子项。

眼动数据空间热点分析图（图7）结果显示，建筑要素的高值区域主要集中在历史建筑较为集中的区域，表明这些区域的建筑风格对游客的视觉吸引力较强；道路要素的高值区集中在街道交汇处和边界明显的地

表 3：建筑要素分类

建筑要素	划分依据
现代建筑	1941 年及之后建造的建筑，多为近代摩登样式
传统建筑	第一次鸦片战争之前（即 1840 年之前）建造的闽南传统民居建筑
西式建筑	19 世纪末到 20 世纪初由华侨建造的建筑，多为西方复古主义或中西结合样式
遗产构件	包括被指定为遗产建筑单体的结构性或装饰性部件

方，因其良好的可视性和空间开阔性，吸引了更多游客的流动和停留，反映出这些区域在游客流动中的重要性；自然要素的高值区则出现在海滩和公园等视野开阔的区域，显示出自然景观对游客的视觉吸引力；而地标要素的高值区则多出现在商住型街道和空间节点——例如，鼓新路和三明路交叉路口被誉为“鼓浪屿最美拐角”——它们的标志性景物吸引了游客的视觉关注。

4.3 街道空间特征－视觉吸引物相关性分析

研究通过街道空间特征指标与视觉吸引物的相关性分析，进一步揭示了物理环境对心理感知的影响（图7，8）。

1）意象性：人群活跃度与道路和植物呈负相关，与商店招牌呈正相关；历史建筑比例和西式建筑、遗产构件、山体／岩石、喷泉呈正相关。这些结果提示，在人群活跃度较高的区域，商业元素如商店招牌可能更吸引受试者的注意力。这是因为商业区域通常具有较多的互动空间和较强的视觉刺激，商业广告和招牌以其色彩和设计风格吸引游客的目光，尤其在商住型街道如龙头路和市场路上尤为明显。与此相反，历史建筑比例较高的街道，如福建路、晃岩路等，因其丰富的历史文化内涵和独特的建筑风格，成为受试者视觉关注的重点。西式建筑和遗产构件通常具有较强的历史象征意义，尤其是在厦门这种具有独特地域文化和历史背景的城市中，历史遗址和建筑的视觉吸引力通常更为突出，传统建筑与西式建筑的结合为游客提供了丰富的视觉体验。

2）围合度：街道宽度与西式建筑、遗产构件、喷泉呈正相关；街道高宽比（同侧）与广场、商店招牌呈现正相关。街道的空间布局和建筑特征影响视觉关注，宽敞的街道能促进对建筑和公共空间的关注，而狭窄街道会增强道路要素的视觉吸引力。在福建路等遗产建筑丰富的街道上，宽敞的街道使受试者的视线不仅集中在具有文化价值的建筑上，还会关注到喷泉等人工构筑物。反之，在三明路等交通型街道上，街道相对狭窄，这种紧凑的空间环境限制了视野范围，使得道路、植物等要素成为视觉关注的主要对象。此外，街道高度、高宽比与商店招牌之间存在正相关性，尤其是在龙头路等商业活跃的街道，较高的建筑和商店招牌更容易吸引视觉注意力，空间布局的差异使其成为关注的焦点。

3）人的尺度：天空开敞度与受试者对天空开敞度的关注度呈正相关；可视域体积与传统建筑、山体／岩石、喷泉等要素的视觉关注呈正相关。在天空开敞度较高的街道，如福建路和晃岩路，传统建筑和自然元素成为明显的视觉焦点，这些元素因其文化和自然价值与周围环境形成鲜明对比，被受试者频繁关注。例如，在可清楚见到日光岩的区域，其独特的自然景观吸引了显著的视觉关注。鼓浪屿作为“万国建筑博物馆”的景观特色不仅体现在建筑风格的多样性上，同时也反映在其周边的山体／岩石、喷泉等自然和人工景观元素上，这些元素可能是历史建筑选址时考虑的一部分，或历史时期景观设计中有意为之的结果。此外，在具有宽广视野的街道上，如安海路，视觉面积占比较大而信息较少的天空更易受到关注。

4）透明性：墙壁占比与围墙／栏杆的视觉关注呈正相关。在狭窄的交通型街道中，墙壁和围墙／栏杆虽然限制了视野，但因其装饰和细节而成为显著的视觉焦点——透明性概念关注的是视觉界面如何允许视线穿透，促进视觉连接和互动，而在视野受限的环境中，由于缺乏这种透明性，受试者的注意力更容易被具有装饰性和细节性的界面所吸引。国际城市设计实践中对透明性的重视也证明了其在空间营造中的重要性。例如，埃及亚历山大市对商业零售建筑的底层开窗比提出了具体要求，不仅提高了街道活动的可见性，也提升了街道环境的活跃度[48]。

5）复杂度：建筑占比与现代建筑呈正相关，与道路、植物、海呈负相关；环境色彩对比与现代建筑呈正相关，与路标／地名呈负相关。在建筑占比较高的街道（如生活型街道），现代建筑以其明艳的色彩对比，成为引人注目的视觉焦点。相对而言，在以路标／地名为主要元素的街道上，为了强化这些导向性元素的辨识度，环境色彩往往更为朴素，以确保信息的有效传达。

4.4 视觉吸引物－生理指标MNL模型分析

为了揭示心理感知与生理指标之间的关系，研究通过MNL模型来量化不同视觉吸引物对生理数据的影响程度。结果显示，仅现代建筑、传统建筑、道路、围墙／栏杆、天空、植物和商店招牌7项视觉吸引物与生理指标之间具有显著关联（表4）。

注视现代建筑时，受试者的生理数据的反应并不强烈，但注视点持续时间与心率变异性呈显著负相关。现代建筑的外观通常具有简洁、规整、线条流畅等特点，与自然景观相比缺乏有机元素和变化，容易使人产生视觉单调感，从而降低了情绪的活跃程度，进而降低心率变异性。

注视传统建筑、围墙／栏杆时，受试者的左右瞳孔直径呈现显著变化。已有研究发现，受试者观看兴趣区内景物时的瞳孔普遍大于其观看兴趣区外景物[17]。瞳孔的扩张可能是因为受试者对传统建筑及其围墙和栏杆的视觉兴趣度较高，而瞳孔的收缩可能与受试者对传统建筑的回忆和认知负荷有关[49]，即观察者需要花费更多的注意力去处理与传统建筑相关的回忆。

道路与皮电和心率结果呈显著正相关，这可能是由于道路上的视觉刺激（如地面铺装和指示标）吸引了受试者的注意，进而导致皮电和心率数据升高。

围墙／栏杆与心率变异性呈显著正相关，即围墙／栏杆的高度和密度越大，心率变异性越高。这是因为高度和密度较大的围墙和栏杆会形成景框效应，使街道透明性减弱，会引起受试者的压抑等不适感，从而引起心率变异性数值的增加。

天空和植物与注视点持续时间呈显著的负相关，已有研究证实，天

表 4：眼动选择行为对生理数据影响的 MNL 模型结果

变量	现代建筑		传统建筑		道路		围墙／栏杆		天空		植物		商店招牌	
	β	*SE*	*β*	*SE*	*β*	*SE*	*β*	*SE*	*β*	*SE*	*β*	*SE*	*β*	*SE*
FPOGD	0.011	0.031	−0.110	0.074	0.043	0.027	0.008	0.026	−0.450***	0.053	−0.071*	0.031	0.064	0.038
LPD	−0.119	0.066	0.363*	0.146	0.110	0.058	−0.205***	0.056	0.087	0.092	−0.047	0.065	0.155	0.084
RPD	0.116	0.066	−0.294*	0.143	−0.112	0.057	0.214***	0.055	−0.174	0.090	−0.022	0.064	−0.240**	0.082
GSR	0.008	0.030	0.015	0.068	0.075**	0.026	−0.025	0.026	−0.185**	0.059	−0.029	0.031	0.084*	0.034
HR	−0.052	0.030	0.100	0.070	0.131***	0.027	0.023	0.025	−0.186***	0.045	−0.043	0.030	−0.034	0.039
HRP	−0.089**	0.033	−0.157	0.082	−0.013	0.027	0.050*	0.025	0.003	0.047	−0.046	0.032	0.105**	0.035
常数项 c	−1.311***	0.030	−3.419***	0.071	−0.749***	0.026	−0.443***	0.025	−2.529***	0.049	−1.303***	0.030	−2.028***	0.038
LR chi^2(6)	15.470		13.270		35.970		23.410		118.730		18.720		23.940	
Prob > chi^2	0.017		0.039		0.000		0.001		0.000		0.005		0.001	
Log likelihood	−3 484.395		−962.746		−4 220.049		−4 502.262		−1 846.143		−3 495.798		−2 429.947	
Pseudo R^2	0.002		0.007		0.004		0.003		0.031		0.003		0.005	

注
1. * 表示 $p < 0.05$，** 表示 $p < 0.01$，*** 表示 $p < 0.001$。
2. 未列出的其他视觉吸引物，回归系数均不显著。

空、绿化等占视域面积比例较大，但信息量较少，因而注视停留较短[50][51]。此外，天空作为一种开放、平静的元素，对皮电和心率结果有着显著的负向影响，即观察天空时皮电和心率数值降低。

注视商店招牌时，右瞳孔收缩，皮电值略有增加，心率变异性显著升高。这是因为对招牌的详细观察需求增加了认知负荷，引起瞳孔收缩[49]；同时，商店招牌引起受试者的兴趣，导致皮电和心率变异性增加。

4.5 心理感知－生理指标回归分析

研究利用OLS回归模型来分析心理感知－生理指标之间的相关性。研究发现仅注视点停留时间、瞳孔直径和心率三个生理指标与心理感知项（封闭－开敞、热闹－冷清、阴暗－光明）表现出显著的统计学相关性（图9），R^2值分别为0.14、0.12和0.11，即模型1解释注视点停留时长变化的14%，模型2解释右瞳孔直径变化的12%，模型3解释心率变化的11%。

开敞度方面，模型1表明注视点持续时间与开敞度的感知存在正向关联，即开阔的街道环境能吸引更多的视线停留，表示宽敞空间可能增强人们的注意力和愉悦感。这与康善之等人的研究相呼应，即开敞空间能带来积极的情绪体验[14]。

街道活力方面，模型2表明热闹感知越强（意味着街道上有更多的视觉兴趣区），瞳孔直径越大，相关研究也证实了街道的户外店招强化了人们的空间兴趣[50]，进而导致瞳孔扩张。

光线方面，模型3显示光亮度感知越强，心率数值越低，表明光线明亮的街道环境可以增强受试者的积极情绪，使人们更加放松和冷静。

5 讨论

5.1 物理－生理－心理作用机制分析

研究围绕历史街道中游客的空间感知及其影响因素这一核心问题，基于虚拟地理环境的历史街道空间感知实验，对物理－生理－心理作用机制进行了总结，包括以下主要结论。

1）物理层面因素，尤其是街道的建筑风格、商业布局、空间尺度和界面透明性，直接影响游客的视觉体验和视觉选择决策。

2）生理指标，如注视点持续时间、心率、瞳孔直径的变化反映了游客对街道中不同视觉吸引物的实时情绪，揭示了历史街道的地域风貌对提升旅游体验的潜在价值。

3）心理层面因素在物理环境与生理反应之间起着桥梁作用。心理感知与生理指标的关联分析证实了视觉选择行为背后的“物理环境—眼动注视—情绪激发”过程，其中，街道空间的开敞度、活力、光线等是提升步行体验的重要因素。

5.2 历史街道空间优化策略

1）交通型街道：此类街道围墙较多，绿化丰富但视觉单调。应增加街道宽度和开敞度，提升围墙的透明度，增强街道的视觉吸引力。例如，可在保证通行效率的同时设置互动设施和展示装置，增强街道的活力。

2）生活型街道：此类街道狭窄，开敞度低，现代建筑密度大，自然要素较少。应充分考虑本地居民生活和游客体验诉求，对生活型街道进行立面风貌整治，提升街道的整洁度和开敞度。例如，可通过建设口袋公园、“见缝插绿”等方式提升生活型街道与自然环境的协调度。

3）商住型街道：此类街道是吸引游客视线的重要空间，店面招牌形式多样，明暗交错。应该加强对街道光线的调控，避免商店招牌导致的光线急剧变化引起游客生理不适；同时加强业态引导，促进现代商业与历史建筑的有机融合。

4）综合型街道：此类街道文化遗产建筑丰富，但出于遗产保护需求，墙壁占比较大，透明性低，互动性较弱。应在保护遗产建筑和构件的同时，提高街道界面的透明性，以吸引人们驻足观察。例如，可借助VR、AR等技术手段，引入历史场景复原、历史建筑虚拟建造、数字遗产展示、虚拟NPC讲解等设施，增强互动体验。

6 结语

本研究采用眼动和生理传感实验，探索历史街道中游客的空间感知及其影响因素，捕捉了个体的视觉关注偏好，并总结了历史街道空间感知的物理—生理—心理作用机制。研究结果表明，在物理层面上，历史街道的建筑和商业要素对游客的空间感知有显著影响，其中，高意象性、低围合度、高开敞度、高透明性和高复杂度的环境特征能够吸引游客的视觉关注并激发情绪反应。生理层面上，心率、瞳孔直径等生理指标表明，在交通型街道中游客更多关注围墙、栏杆等要素，在商住型街道中则偏好商店招牌，在生活型街道中更关注现代建筑，而在综合型街道中更偏好传统建筑，尤其是其遗产构件和自然要素。心理层面上，受试者对历史街道的开敞度、活力、光线的心理感知也反作用于生理反馈，环境的视觉吸引力和情绪激发能显著影响个体的眼动选择行为。

本研究提出的“物理—生理—心理”空间感知研究路径，丰富了环境心理学理论在历史街道研究中的运用，也为历史街道步行性研究提供了新的视角。在方法上，本研究构建了三维虚拟地理环境，采用眼动追踪和生理传感实验，为历史街道环境感知研究提供了一种新的量化方法，提升了研究的精确性。在应用上，为鼓浪屿四种类型的历史街道提供了人本视角的城市更新策略。

本研究尚存在一些不足，未来研究需进一步评估三维虚拟地理环境的还原度，改进实验设备流畅性，如采用头戴式VR眼动跟踪系统。同时，应将本研究框架应用至更多历史街道，运用深度学习技术，提高数据分析精度和效率，以丰富历史街道优化策略。

致谢

感谢厦门市规划数字技术研究中心、厦门市鼓浪屿–万石山风景名胜区管理委员委会为本研究提供鼓浪屿三维模型基础数据和参考资料。感谢匿名审稿专家的细致审阅和宝贵意见。

图 1. 历史街道空间感知研究路径
图 2. 研究路线（基于厦门市自然资源和规划局标准地图服务网站厦 S〔2022〕05 号标准地图制作）
图 3. 41 名受试者实验截图
图 4. 受试者对虚拟场景真实性还原度评价调查示例。该调查的评分标准为 1 分（最低）至 5 分（最高）。
图 5. 空间感知调查问卷示例
图 6. 生理数据热点分析（基于厦门市自然资源和规划局标准地图服务网站厦 S〔2022〕05 号标准地图制作）。
图 7. 眼动视觉关注要素热点分析（基于厦门市自然资源和规划局标准地图服务网站厦 S〔2022〕05 号标准地图制作）。
图 8. 空间特征指标与视觉吸引物相关性分析结果（* 表示在 0.05 的水平上显示显著相关性，** 表示在 0.01 的水平上显示显著相关性，*** 表示在 0.001 的水平上显示显著相关性）。
图 9. 心理感知与生理传感数据回归分析