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Visual Perception Differences and Spatiotemporal Analysis in Commercialized Historic Streets Based on Mobile Eye Tracking: A Case Study in Nanchang Wanshou Palace, China

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Abstract: The commercialization of historic streets constitutes a pivotal aspect of urban cultural heritage, and the comprehension of their visual perception serves as a valuable asset to urban planning and cultural conservation efforts. However, current research concerning the disparities in visual perception among diverse demographics within historic streets, as well as their spatiotemporal dynamics, remains insufficient. This study aims to utilize mobile eye-tracking technology to delve into the visual perceptual characteristics of diverse individuals within commercialized historical urban areas. It seeks to analyze the spatiotemporal dynamic shifts, observing how people's visual perception and focal points of attention evolve alongside the changes in time and space within these commercialized historical districts. We examined the differences in the visual perception of historical urban areas among groups with varying degrees of architectural knowledge and professional expertise, using the example of the Wanshou Palace Historic Cultural District in Nanchang. Through meticulous observation using mobile eye-tracking technology, we elucidate the visual perception patterns of different demographic characteristics through statistical analysis and spatiotemporal modeling. The findings reveal significant discrepancies in visual attention and perception among various groups. Participants with a deeper understanding of architecture tend to fixate on the architectural details and structures within the urban district, with architectural elements garnering a significant share of 68.6% of their visual attention. Conversely, individuals with a lesser comprehension of architecture exhibit a greater interest in shops and signage elements, with architectural elements receiving a mere 59.23% of their visual focus, while commercial elements attract a significant 25.7% of their attention. Moreover, during the process of perceiving the streetscape, participants' eye movements transition from surrounding landscapes and historical edifices upon initial entry to the district, gradually shifting towards the commercial activities and distinctive architecture within the district. This study delves deeply into the visual perception characteristics and spatiotemporal dynamics of commercialized historic streets, providing invaluable insights for urban planning and cultural preservation endeavors. By revealing the impact of different demographic characteristics on the visual perception of historic streets, it offers new insights for urban planning and cultural heritage conservation.

Keywords: historic streets; environmental attractiveness; visual perception; temporal shifts in attention; mobile eye-tracking technology

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1. Introduction

Historic streets, as essential components of urban culture, bear a wealth of historical memories and cultural value [1]. With the passage of time, many historic streets have gradually integrated commercial elements, forming unique commercialized historic districts. These districts are not only a part of the daily lives of local residents but also attract numerous tourists. Historic streets, due to their profound cultural heritage and distinctive character, have become hotspots for urban tourism, promoting the development of the tourism industry and driving local economic growth [2–4]. Additionally, historic streets play a crucial role in maintaining the urban cultural context and perpetuating historical memories [5,6]. They serve as a link between the past and the present, providing a vivid manifestation of urban history, allowing history to be tangibly embodied in contemporary society. Over the years, many scholars, both domestically and internationally, have conducted in-depth research on the perceptions of different demographics regarding commercialized historic districts through methodologies such as surveys, in-depth interviews, and behavioral observations [7]. Eye-tracking technology can objectively record eye movements, providing millisecond-level tracking responses, accurately capturing individuals' rapid cognitive processes and environmental interactions [9**?**]. In recent years, it has been widely applied in fields such as aesthetic perception and landscape environment evaluation. In the realm of aesthetic perception, researchers have delved deeply into users' perception processes of urban aesthetics from various perspectives, including but not limited to comparing individuals' eye movement data when observing urban aesthetics across different age groups, genders, cultural backgrounds, and socioeconomic statuses, revealing how these sociodemographic factors influence individuals' visual attention and aesthetic preferences [10]. Researchers have also evaluated the importance of various aesthetic elements in aesthetic perception and proposed concepts such as "information density" to quantitatively describe the visual information content of different elements [11]. Furthermore, through eye-tracking experiments conducted across different seasons and time periods, researchers have analyzed how temporal factors affect individuals' perceptions and evaluations of urban aesthetics [11–13]. In aesthetic perception research, researchers have utilized eye-tracking technology for multidimensional in-depth analyses, providing new perspectives and methodologies for understanding the visual cognitive processes of urban aesthetics, while also offering valuable insights for urban planning and design practices.

For the visual perception and behavioral activities within commercialized historic cultural districts, cognitive experiments and analyses were conducted based on observational research. Various experimental models and evaluation systems were developed, and data were collected through methodologies such as surveys, in-depth interviews, and VR (virtual reality) eye-tracking technology. Data were processed and analyzed using methodologies such as deconstructionism [14], system dynamics modeling [15], ridge regression, and lightGBM [16], ultimately yielding a correlation scale elucidating users' visual perception and behavioral activities. In terms of the perception of street aesthetics, researchers have unveiled how different users perceive street aesthetics, identifying both their general preferences and personalized demands [17]. Methods for quantifying street activities were developed [18], including the utilization of eye-tracking technology to quantify the allocation of visual attention and the assessment of the social and economic benefits of street activities through surveys and in-depth interviews [19]. Strategies based on user perception and behavioral activity data were proposed to promote the long-term conservation and revitalization of historic cultural districts.

However, current research on the perception of commercialized historic districts still lacks sufficient analysis of the microdynamic aspects of pedestrians' visual attention allocation and behavioral decision making, failing to fully elucidate pedestrians' attention in street spaces and the underlying perceptual mechanisms. Given that human perception of the surrounding environment and recognition of physical environments are predominantly realized through visual processing, this study employed eye-tracking apparatuses for testing experiments. By discerning subjects' ocular movements, the eye tracker adeptly recognizes and captures subjects' visual foci, correlating their behavioral engagements with specific elements of commercialized historic streets to cogently comprehend the cognitive processes. In recent years, numerous studies have examined the perception of commercialized historic districts from the perspective of tourists [15,20]. However, past studies often treated tourists as a homogeneous entity [21], without subdividing or categorizing them, and tourist cohorts exhibit significant variances. The demographic variance among tourists visiting commercialized historical districts is quite pronounced. We surmise that individuals from diverse occupational and educational backgrounds perceive these districts differently. This study classified participants into three groups based on their architectural knowledge and professional qualities. One group consisted of individuals with expertise in architecture, possessing a certain level of architectural knowledge and professional acumen, enabling them to comprehend and analyze the characteristics of commercial historic districts from a professional perspective. The other two groups included individuals from adjacent fields of architecture, who had some background knowledge of architecture, and those who had no prior knowledge of architecture. In research on the perception of commercialized historic districts, predecessors primarily focused on changes in subjects' focal points spatially, with limited research on changes in subjects' focal points over time. Building upon previous research, this study introduced the concept of a temporal axis, focusing on subjects' primary focal points and the shifts of focal points over time, with the aim of providing insights for the commercial transformation of historic districts.

Taking the Nanjing Wanshou Palace Historic Cultural District as an example, subjects from the three defined groups wore head-mounted eye-tracking apparatuses for experimental data collection. The experimental data were analyzed using the VIT model, resulting in descriptions of the ocular movement patterns of different subject groups, disparities in the visual perception of commercialized historic street aesthetics among different subject groups, and the regions of interest and durations of gaze for different subject groups. The purpose of this study was to understand the visual perception of commercialized historic street aesthetics among different demographic groups. Specifically, research questions included: (1) establishing a research methodology based on eye-tracking technology for the visual perception of commercialized historic districts; (2) exploring the perception of commercialized historic street aesthetics and the differences in the perception of various constituent elements among different demographic groups; (3) formulating methods for identifying the primary focal points of different demographic groups and delineating the shifts of focal points over time. The structure of the entire manuscript is organized as follows: Section 2 provides a comprehensive literature review of the application of eye-tracking technology in the architectural field and research on the perception of commercialized historic districts. Section 3 explains the principles of head-mounted eye-tracking apparatuses, detailing the design and procedures of the experiments, including subject selection and data processing and analysis. Section 4 describes the experimental results and draws three conclusions regarding the perception of commercialized historic districts. Finally, Section 5 interprets the research findings, articulates the limitations of the study, and suggests future research directions.

2. Related Work

2.1. The Application of Eye-Tracking Technology in the Built Environment

Eye-tracking technology, by capturing and recording human ocular activities, offers a unique research tool across various academic domains. Its applications in fields such as medicine, design, education, transportation engineering, and architecture are increasingly expansive, providing novel perspectives for understanding human behavior and cognition [22]. In the realm of medicine, this technology is employed to identify autism spectrum disorder (ASD), utilizing the analysis of eye movement data in afflicted children to furnish new insights for diagnosis and treatment. Within the discipline of design, monitoring subjects' ocular movements across different styles of armchairs aids designers in better comprehending user preferences, thereby guiding design practices [23]. In the field of education, the utilization of head-mounted displays and immersive virtual reality (IVR) environments, coupled with eye-tracking technology, facilitates the optimization of learning experiences [24]. In transportation engineering, eye-tracking technology is widely utilized in studies of driving behavior, revealing the visual cue utilization and awareness levels of drivers during urban driving, high-speed maneuvering, autonomous driving handover requests, and recognition of unfamiliar traffic signs. This knowledge holds significant practical application value for the development of multimodal interactive interfaces tailored to driver characteristics [25], optimization of driver assistance systems [26,27], and enhancement of road traffic safety [**?**].

In the discipline of architecture, the application of eye-tracking technology is becoming increasingly prevalent, offering new perspectives and methodologies for understanding architectural space perception, architectural space interaction, and architectural heritage preservation. Among these, studies on architectural space perception encompass aspects such as urban landscape perception, urban street element perception, and historical area ambience perception. One study utilized VR eye-tracking technology to deeply analyze subjects' visual perception behaviors in the historic cultural district of Zhangzhou, providing a new perspective for understanding how people perceive urban ambience and revealing differences in visual attention behaviors among individuals of varying backgrounds, thereby scientifically supporting ambience preservation efforts [10]. Another study, by observing pedestrians' visual interactions with urban street edges during routine tasks, provides empirical insights for urban street design, emphasizing the importance of considering the visual allure and social functions of street edges in planning and design [19]. This study not only corroborates findings regarding the importance of visual perception from previous research but also further refines the understanding of how urban street elements influence pedestrian visual attention, thereby furnishing empirical data based on user visual behavior for urban street design. Additionally, eye-tracking technology has been implemented in various fields such as urban planning and landscape architecture, indoor environmental assessment, and heritage management. In the domain of urban planning and landscape design, a study employed eye-tracking technology in tandem with online surveys to dissect the correlation between the ratios of different landscape elements and the public's evaluation of the appeal of urban green spaces [29]. Another investigation delved into how landscape complexity influences preference ratings and eye movements within various urban green space configurations, utilizing eye tracking to analyze visual attention and preferences when observing different types of urban greenery, including lawns, pathways, plazas, and waterfronts [30]. This study offered additional insights into the specific ways in which people perceive and assess different landscape elements within urban green spaces, thereby enhancing our comprehension of the factors that determine the attractiveness of these areas. In the realm of indoor environmental assessment, a pilot study utilizing eye tracking within a virtual reality setting examined the impact of greenery elements in office environments on cognitive performance, visual attention, and distractions [31]. In the area of heritage management, a study conducted eye-tracking tests to compare the predictions of experts regarding how informational signage affects the perception of historical monuments with the actual visual reactions of viewers. The eye-tracking findings indicated that experts have limitations in forecasting viewers' responses to changes in the color of signage, suggesting that the use of eye-tracking technology may be essential in the management of historical structures [32].

Building upon this foundation, a study focusing on the Nanjing Road pedestrian street quantitatively analyzed pedestrians' attention distribution using head-mounted eye-tracking technology. The introduction of the "information density" metric in this study provides a new quantitative method for assessing the efficiency of environmental elements in attracting attention, complementing the methodological framework for quantitative analysis of visual perception in previous studies [11]. In the field of architectural space interaction, a study employing automated deep learning methods offers a new technical framework for quantitatively exploring the correlation between street architectural environments and street vitality. This study, integrating GIS analysis, semantic segmentation, as well as deep learning-based scene classification and multi-object tracking, provides a new technical means for the quantitative evaluation of street vitality, not only offering new perspectives for understanding urban space but also furnishing powerful tools for urban planning and design [7]. In the domain of architectural heritage preservation, eye-tracking technology is utilized to study people's visual behavioral characteristics regarding architectural heritage. Studies have found correlations between observers' visual behaviors and various geometric features of architectural heritage, such as area, relative area, distance from the center, and perimeter, which hold significant implications for understanding and preserving architectural heritage [21].

2.2. Perception of Commercialized Historic Streets

Preserving the historic streets as vital conduits of urban culture and commercial activity encompasses multifaceted research, including block renewal design, perception and evaluation of the districts, and preservation efforts. In the realm of block renewal design, significant strides have been made, exemplified by a study employing deconstructivist research methods to deeply analyze Suzhou's Pingjiang Road and Shantang Street. This study, augmented by questionnaire surveys and in-depth interviews, aims to better cater to the needs of both tourists and residents, fostering more effective spatial design and utilization [14]. Not only does this method unveil the construction of cultural, leisure, and scenic spaces, but it also proposes an innovative tourist spatial organization model, termed the "Eight Paths" model. Furthermore, researchers have proposed renewal methods applicable to traditional commercial streets in city centers, aiming to provide practical reference and guidance for the transformation of relevant commercial districts [20]. This endeavor supplements the empirical application of the aforementioned deconstructivist study, enhancing its applicative value and operationality in the practice of historic street renewal, thus establishing a direct linkage between theory and practice. Additionally, research has explored factors influencing block renewal choices and developed strategies aimed at maximizing the interests of three-party stakeholders by combining evolutionary game theory models and system dynamics models [15]. This study not only provides a new analytical framework for block renewal but also offers strategic guidance for maximizing interests through simulating and predicting changes in stakeholders' behavior. This complements the deconstructivist study [14] and traditional commercial street renewal methods [20], with the former focusing on theoretical innovation and spatial design while the latter on practical operation and implementation. The application of system dynamics and evolutionary game theory provides decision support and dynamic management tools for these theories and methods. In the domain of perception and evaluation, researchers utilized Xiamen's Shapowei Historic District as a case study, employing a multi-mode analysis using the Global Positioning System (GPS) and Geographic Information System (GIS). This systematic research examined the impact of architectural environments on street vitality and evaluated residents' spatial perception, street visual allure, and commercial activity attractiveness through the analysis of pedestrian time and spatial data. The findings aid in identifying and understanding the environmental elements and rules behind highly vital street spaces [33]. Another study employed deep learning and machine learning frameworks to assess the landscape spatial quality of streets in Fuzhou, offering a new perspective for urban landscape improvement [34]. By quantifying the spatial quality of urban streets, this study provides a scientific basis for urban planning and construction, complementing the street vitality evaluation system proposed in previous research and providing technical support for the landscape improvement and spatial optimization of historic streets. In the realm of preservation, researchers combined cartography, linguistics, and fractal geometry to evaluate the characteristics of Liverpool Street and Kingsway Street in Ghana's Cape Coast and subsequently proposed preservation measures for these two streets [35,36].

For the study of spatial perception in commercialized historic streets, reliance on traditional methods such as questionnaire surveys, interviews, and behavioral observations often lacks a profound understanding of pedestrians' visual attention allocation and decision-making processes at the micro level. To address this research gap, this paper proposes an innovative solution by applying eye-tracking technology to the field of spatial perception in commercialized historic streets. Compared to traditional methods, eye-tracking technology provides real-time and dynamic data, enabling a more accurate understanding of subjects' spatial perception and revealing the inherent mechanisms of district ambience perception. Through this advanced technology, researchers can precisely capture subjects' visual focal points, evaluate their cognition and reactions to district ambience elements, thereby understanding the visual perception of commercialized historic streets by different groups, and providing more detailed and profound guidance for the design of commercialized historic streets.

3. Method

3.1. Overview

The present study employed on-site eye-tracking experiments utilizing the Tobii Glasses 2 eye tracker. Participants wore the eye-tracking device and freely navigated within the real-life experimental scope of the commercialized historic streets. The experiment, conducted over a period of time, aimed to authentically replicate pedestrians' daily visual cognitive states within the commercialized historic streets, comprehensively understanding the visual cognitive process in both spatial and temporal dimensions. While capturing participants' eye movements at different spatial locations, the experiment also recorded their attention allocation and visual attention pathways at different time points.

The overall experimental methodology, as illustrated in Figure 1, primarily consisted of four steps. (1) Site Selection: The experiment selected the Nanjing Wanshou Palace Historic and Cultural District, characterized by its typicality and representativeness, as the experimental site. This area successfully integrates traditional elements with modern commercial models, forming an attractive commercialized historic street. (2) Data Collection: Participants were divided into three groups based on their level of architectural knowledge and professional expertise. Each group wore Tobii Glasses 2, a head-mounted eye tracker, and, without being restricted by predetermined tasks, freely walked along a given route. Eye movement data were collected using infrared light reflection technology. (3) Data Analysis: Employing the eye-tracking interest area analysis method, the eye movement data were semantically segmented using the ViT model to calculate the cumulative gaze duration and proportion within the areas of interest. Through time series and spatial location analysis, time windows were delineated to study gaze paths, thereby revealing participants' visual attention patterns and preferences. (4) Results Analysis: This study delineated the eye movement patterns of different participant groups, identified differences in visual perception of the commercialized historic street ambience among these groups, and analyzed the identification and duration of gaze on key areas of interest.

3.2. Experimental Design and Procedure

3.2.1. Selection of Sites and Participants

The present study selected the Wanshou Palace Historic and Cultural District in Nanchang City, Jiangxi Province, as the research setting, as depicted in the location map shown in Figure 2. As one of Nanchang City's historical and cultural landmarks, the Wanshou Palace Historic and Cultural District holds significant status and represents the city's rich heritage. Situated in the heart of Nanchang City, this district boasts a long history and profound cultural heritage, serving as one of the city's important historical sites and cultural attractions. Designated as a protected area, it is subject to stringent conservation measures aimed at maintaining its architectural authenticity and cultural integrity. The Wanshou Palace Historic and Cultural District derives its name from the renowned Wanshou Palace, a significant historical site within the area. Managed by local authorities and heritage preservation organizations, the district's management focuses on balancing preservation efforts with commercial activities, ensuring sustainable development while safeguarding its historical essence. The district's relevance extends beyond its historical significance, serving as a vibrant cultural hub and tourist attraction. Integrating traditional architectural charm with modern commercial elements, it attracts visitors from far and wide, contributing to the city's cultural vitality and economic growth. The Wanshou Palace Historic and Cultural District exemplifies successful heritage preservation and adaptive reuse, showcasing the harmonious coexistence of tradition and modernity. Its typicality and representativeness effectively showcase the characteristics of commercialized historic streets and the visual cognitive process of pedestrians.

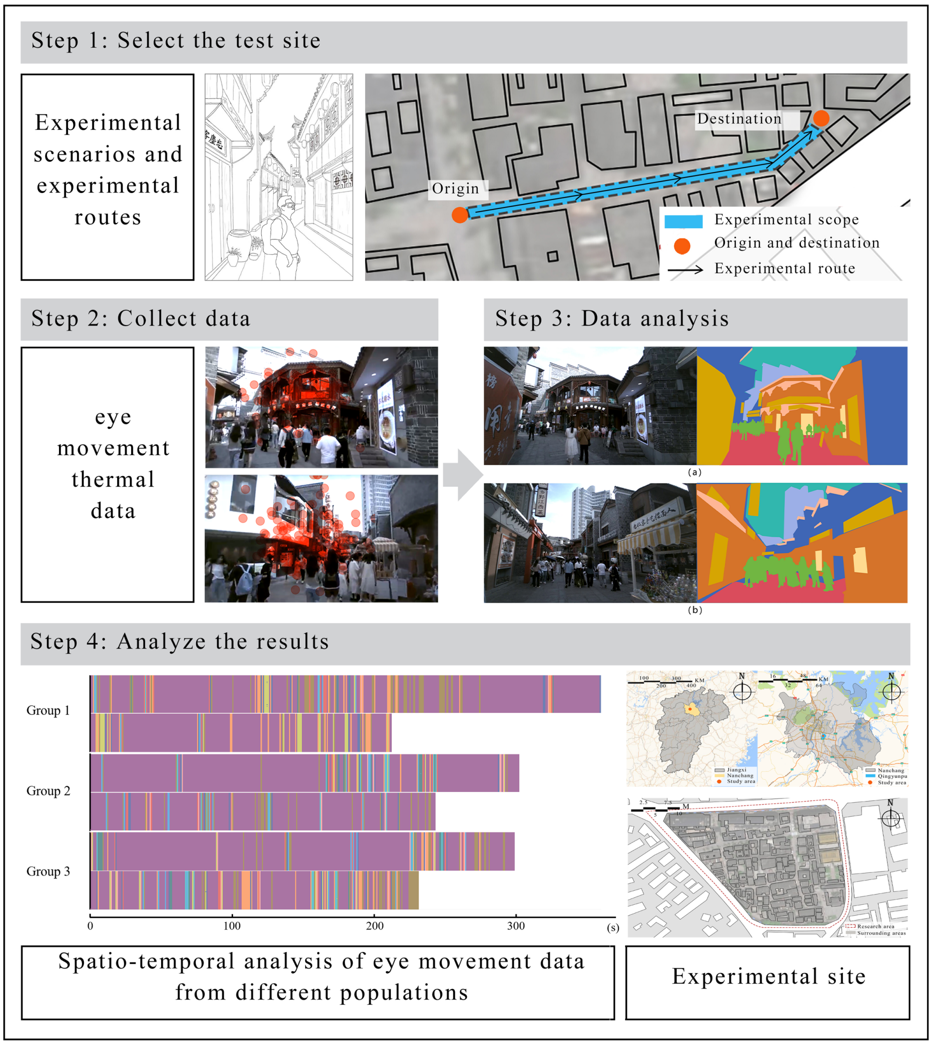

Figure 1. The overall framework of the study on the perception of commercialized historic streets: It elucidates the process of data collection using eye-tracking technology, followed by data analysis employing methods such as interest point identification and semantic segmentation.

The main task route distribution is illustrated in Figure 3, showcasing a rich blend of ancient architecture and commercial elements such as shops and signage, effectively reflecting the situation of the commercialized historic street. Moreover, it traverses through the commercialized historic district, providing a comprehensive insight into the visual perception changes of visitors upon entering the commercialized historic area, based on the timeline of eye-tracking data. Through the analysis of eye-tracking data along the timeline, it reveals pedestrians' varying levels of attention to the environment during different time periods, their interest levels in specific landscape elements, and the timeline of their behavioral decisions, thus offering a more comprehensive understanding of pedestrians' visual cognitive processes in the commercialized historic district.

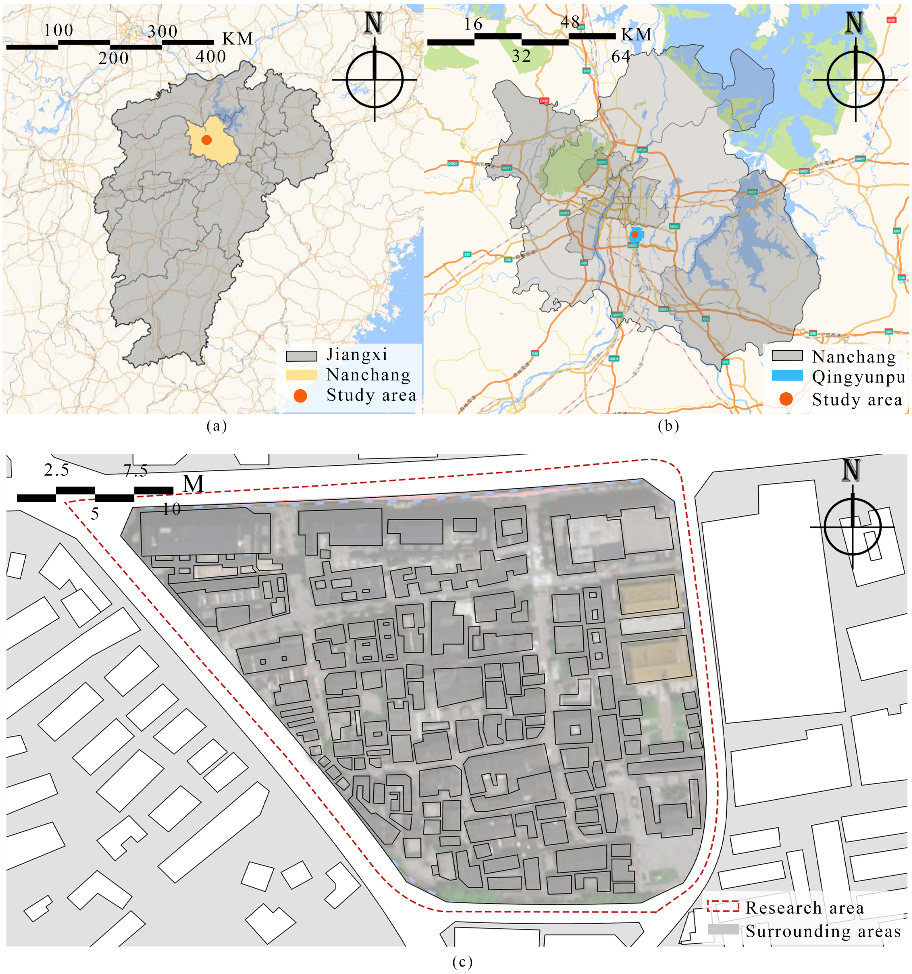

Figure 2. The map of the research area. (**a**) the location of Nanchang City within Jiangxi Province; (**b**) the position of the study site in Nanchang City; (**c**) the research site: Wanshou Palace Historical and Cultural Block.

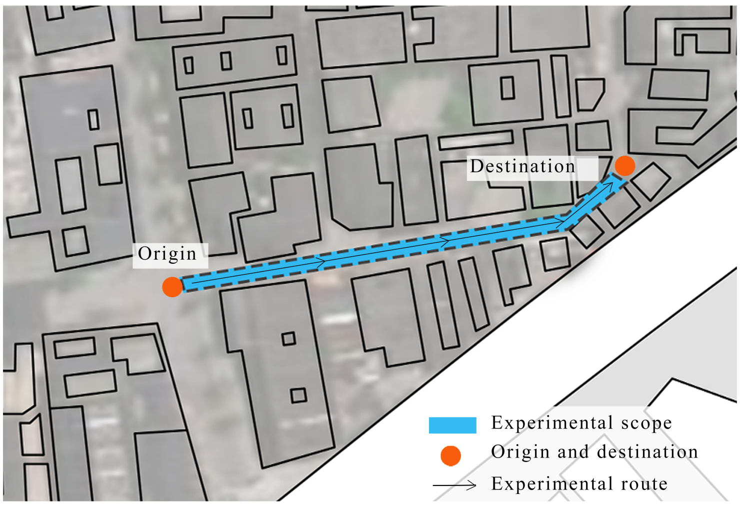

Figure 3. Illustration of the selected experimental route segment.

Three groups of participants were selected for this study, each comprising three individuals. During participant selection, a questionnaire was used to determine their level of architectural knowledge and professional expertise based on self-assessment and responses to architectural questions. One group consisted of participants with a background in architecture, possessing certain architectural knowledge and professional literacy, enabling them to understand and analyze the characteristics of commercialized historic streets from a professional perspective. The other two groups included individuals from architecture-related fields (disciplines closely related to architecture, including urban planning, civil engineering, landscape architecture, and interior design) with some architectural knowledge, and those with no architectural background, representing the general public. This design ensured that the research results were more comprehensive and representative, delving into the visual cognitive characteristics of commercialized historic streets from different perspectives.

3.2.2. Experimental Procedure

Participants were first required to complete a basic information questionnaire, which included questions about their self-assessment of architectural knowledge and professional literacy, basic architectural questions, and their familiarity with the WanShou Palace Historic Cultural District. Following this, participants were given a brief introduction to the history, significance, and main features of the street to assess their prior knowledge. Following familiarization with the overall environment and basic routes of the WanShou Palace Historic Cultural District, participants wore and calibrated the eye tracker. Subsequently, participants conducted on-site inspections along the assigned route map at the same time of day. During this process, they were free to walk and observe while the eye tracker recorded eye movement data. After the experiment, participants filled out a questionnaire regarding their experience and feedback, facilitating further analysis of the experimental results, conclusion drawing, and improvement suggestions. The entire experimental process lasted approximately 5 min to ensure that participants had sufficient time to observe and experience the on-site environment.

3.3. Data Collection and Analysis Techniques

3.3.1. Collection of Visual Perception Data

The visual perception data were collected using the Tobii Glasses 2 eye tracker, as illustrated in Figure 4. The detailed specifications of the Tobii Glasses 2 eye tracker are provided in Table 1.

Table 1. The detailed specifications of the Tobii Glasses 2 eye tracker.

Eye tracking technology specifications	
Eye tracking	Corneal reflex, binocular stereo dark pupil tracking
Binocular tracking	Yes
Sampling frequency	50 Hz or 100 Hz
Calibration method	System-guided, one-point calibration
Parallel inspection calibration tool	Automatic
Slip compensation	Automatic, 3D eyeball model
Pupillary measurement	Support, absolute measurement
Head mounted module	
Number of eye-tracking cameras	4 eye-tracking cameras 16 infrared light sources
Sensors	Gyroscope accelerometer Magnetometer
Scene camera video format and resolution	H.264 1920 × 1080 @25 fps
Scene camera perspective	Ultra-wide angle 106° (16:9)
Scene camera recording angle/perspective	95° horizontal, 63 vertical
Frame size	153 × 168 × 51 mm

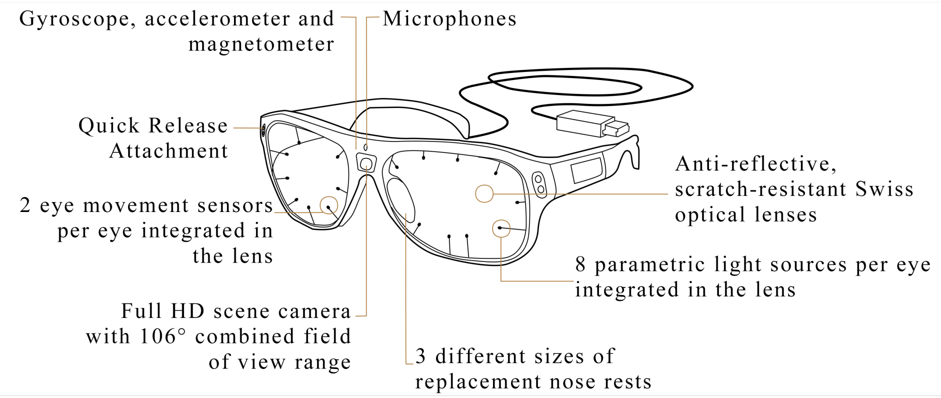

Figure 4. Schematic diagram of the mobile eye tracker.

As depicted in Figure 5, the eye tracker utilizes infrared light reflection technology to collect eye movement data.

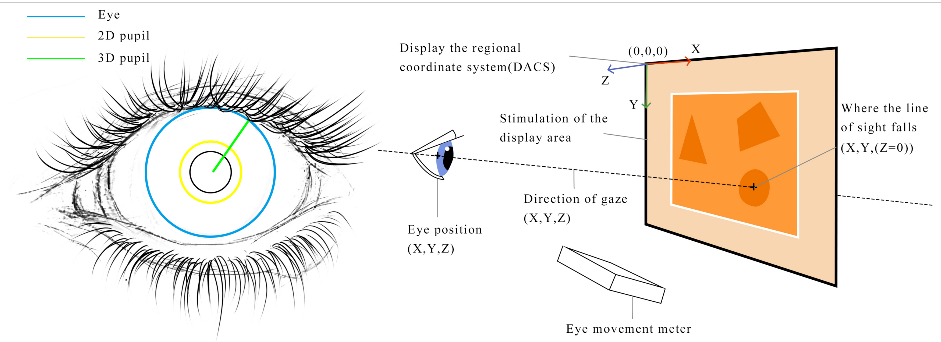

Figure 5. The range of ocular activity and the principle of operation of the eye tracker.

Specifically, the eye tracker is equipped with an infrared light source that emits infrared beams directed towards the subject's eye surface. Subsequently, the internal camera of the eye tracker captures the infrared light reflected from the surface of the eye. By processing the captured reflection light, the eye tracker can calculate the position and trajectory of the eye within the camera's field of view. These collected eye position data are then recorded for subsequent analysis and research. The process is outlined as follows: Firstly, the eye tracker emits infrared light directed towards the subject's eye surface. Secondly, the infrared light reflected from the eye surface is captured by the internal camera of the eye tracker. Next, by processing the captured reflection light, the eye tracker calculates the position and trajectory of the eye within the camera's field of view. These data points are recorded at regular intervals, forming a series of eye position data. The formula for this process is as follows:

$$P_{i,j} = f(l_{i,j}) \tag{1}$$

Here, $P_{i,j}$ represents the eye position data recorded at time i and position j, while $l_{i,j}$, denotes the intensity and direction of the captured eye reflection light. The conversion function f is employed to transform the captured reflection light data into eye position data.

By correlating eye-tracking data with the images viewed by the participants, we can obtain insights into their eye movements over a period of time. This matching process reveals the visual points of interest and gaze paths of the participants when observing a particular scene or object, thereby providing crucial reference data for understanding the process of visual perception and cognition.

3.3.2. Data Processing

In this study, we employed a method that combines eye-tracking data with both temporal and spatial dimensions to delve deeper into the visual cognition process of participants in the commercialized historical street area. For the analysis of pure eye-tracking data, we utilized the eye-tracking area of interest analysis method [37], defining specific areas or elements of interest as eye-tracking areas and calculating the cumulative gaze duration and proportion within these areas. However, due to the large volume of eye-tracking data collected, manual frame-by-frame analysis is time-consuming and labor-intensive. Therefore, our study employed a method that combines automatic semantic segmentation to assist in data processing. For the acquired eye-tracking data, images and gaze coordinates were extracted every 0.5 s as individual time points. Semantic segmentation was then performed on the images, utilizing transfer learning with the ViT model [38]. We trained the model using the ADE20k street scene database [39] to enhance segmentation accuracy for street scene data [40]. After segmentation, a mask matrix of image elements was obtained, as illustrated in Figure 6. By matching gaze coordinates with the mask matrix, we statistically analyzed the elements of interest at each time point and their proportion within the field of view.

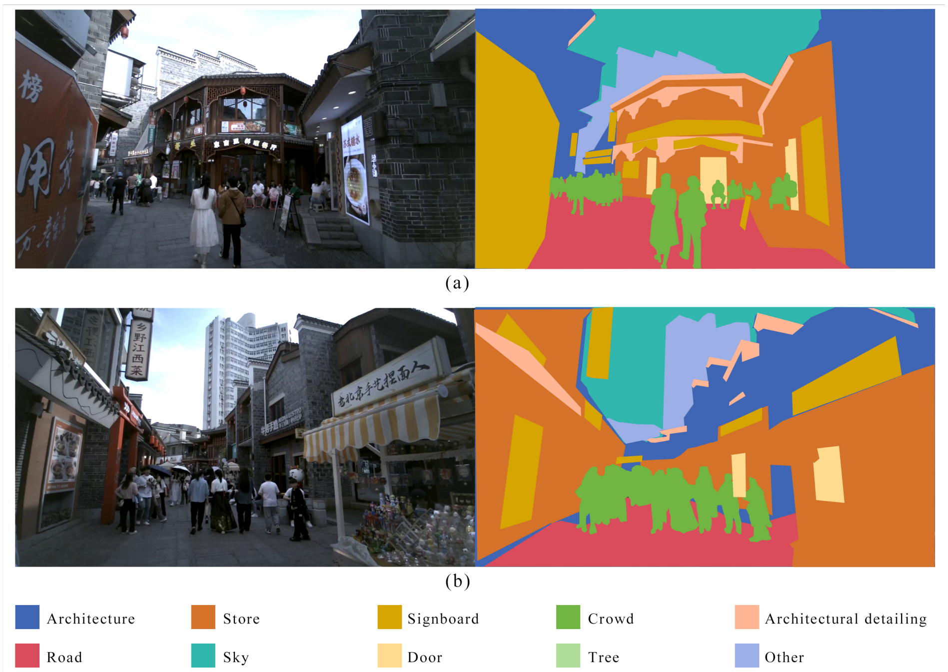

Figure 6. Semantic segmentation of environmental elements ((**a**,**b**) are street view images and semantic segmentation images of different parts of the street).

Building upon the processing of data at individual time points, this study conducted a cohesive analysis of participants' gaze patterns over time and space throughout the entire experimental process. For the time series analysis, the study divided the entire experimental process into multiple time windows and assessed participants' gaze patterns within each window. By comparing gaze distributions across different time windows, the aim was to reveal participants' visual attention preferences and attentional allocation at different stages of the experiment. Regarding spatial location analysis, the study analyzed participants' gaze preferences and attentional allocation at different locations based on their spatial positions at various time points.

4. Result

4.1. Description of Eye Movement Patterns across Different Participant Groups

As depicted in Figure 7, different groups of participants exhibit distinct gaze patterns. Among participants with a background in architecture, their gaze duration prioritizes architectural elements, followed by commercial, road-related, landscape, and other elements. These participants tend to perceive the overall spatial and architectural forms first, seeking characteristic elements from spatial compositions and aesthetic forms. The gaze duration on architectural elements accounts for 68.6%, with overall architecture at 63.1% and architectural details at 5.5%. Based on participants' verbal feedback during the tests, their attention to architectural details ranks as follows: eaves, doors and windows, pillars, and archways. Over 50% of participants showed prolonged attention to specific architectural elements, indicating heightened interest in the area.

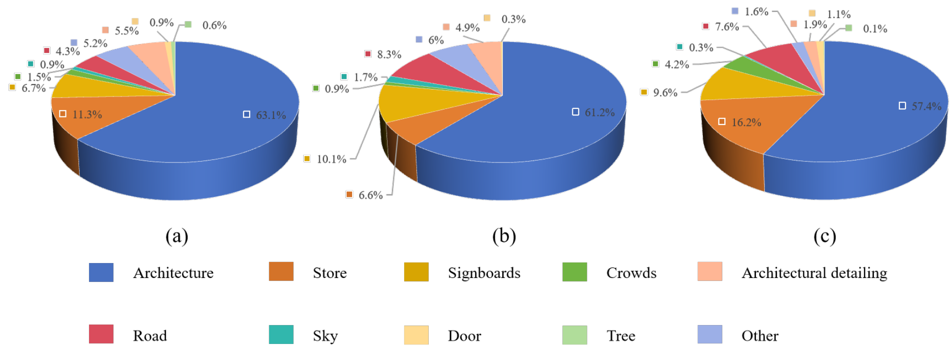

Figure 7. Pie chart depicting the distribution of gaze among different groups: (**a**) participants with a background in architecture; (**b**) participants with some architectural knowledge; (**c**) participants with little to no architectural background.

For participants with a background in architecture, architectural elements have the highest gaze duration proportion at 66.1%, while landscape elements have the lowest at 1.7%. Their gaze scan rate is higher, covering a wider spatial span with shorter average dwell times. This is because these participants have some architectural knowledge, reducing their unfamiliarity with commercial and road-related elements in the district. Familiar commercial activities and road facilities do not capture significant interest during their walk through the district. Landscape elements, due to their limited relevance to participants' activities, maintain a lower level of attention.

Participants with little to no knowledge of architecture exhibit gaze durations prioritizing architectural, commercial, road-related, landscape, and other elements. Their gaze tends to focus on smaller objects below the eye level. Although architectural elements still dominate in gaze duration proportion at 59.2%, participants in this group did not show significant interest in these elements during the experiment, possibly due to the extensive visual presence of architectural elements in the district. Commercial elements have a gaze duration proportion of 25.7%, indicating strong interest in various commercial activities. These participants often pause in front of commercial stalls during their walk, reflecting their curiosity about commercial activities.

4.2. Analysis of Visual Attention Discrepancies towards Commercialized Historic Streets Capes

At the level of overall elements, the tested individuals demonstrate varying degrees of attention to the elements of the streets, namely architectural elements, commercial elements, roadway elements, landscape elements, and other elements. Due to the differing characteristics of the segmented population, there are certain differences in the specific levels of attention to various elements among the three groups.

Individuals with a higher level of architectural knowledge tend to exhibit greater attention to architectural elements, likely due to their deeper appreciation and interest in the historical and cultural value of architecture. Compared to the other two groups, those with a background in architecture demonstrate a greater interest in the finer details of architectural construction. In terms of commercial elements, all three groups exhibit a relatively high level of attention, with percentages of 18.0%, 16.7%, and 25.7%, respectively. This is because commercial activities on the streets are closely linked to the actions of different groups of people, thereby influencing pedestrian activities. Among them, the group that is completely unfamiliar with architectural knowledge demonstrates the highest level of attention to commercial elements, possibly because the other two groups have a better understanding of the commercial activities in historic streets, whereas this group has less knowledge about the scene, leading to a stronger sense of novelty and thus greater interest. Regarding roadway elements, there are significant differences in attention levels due to varying degrees of familiarity with the environment. The attention rates for individuals from architecture backgrounds, those with some architectural knowledge, and those with little to no architectural knowledge are 4.3%, 8.3%, and 7.6%, respectively. This is because the entire area is more unfamiliar to individuals with little to no architectural knowledge, making them more interested in exploring the unfamiliar environment during their walks. In terms of landscape elements, since they have less relevance to the activities of the tested individuals, the attention levels remain relatively low.

4.3. Key Areas of Interest and Duration of Fixations

Considering that the duration of environmental elements being fixated largely depends on their visual area [41], to objectively reflect the level of attention attracted by each element, this study introduces the concept of "information density" [11]. Information density is defined as the ratio of fixation percentage to pixel exposure percentage, with the specific formula as follows:

$$attention\ percentage = \frac{D_i}{\sum_n^{j=1} D_i} \tag{2}$$

$$pixel\ percentage == \frac{A_i}{\sum_n^{j=1} A_i} \tag{3}$$

$$information\ density = \frac{attention\ percentage}{pixel\ percentage} \tag{4}$$

Certainly, D_i represents the cumulative fixation time for the ith element, $\sum_n^{j=1} D_i$ represents the total cumulative fixation time for all n elements in the frame, A_i represents the objective visual area of the ith element, and $\sum_n^{j=1} A_i$ represents the total objective visual area for all n elements in the frame. This metric serves to quantify the attractiveness of a particular element in the visual environment. Table 2 illustrates these environmental elements along with their corresponding fixation percentages, exposure percentages, and information densities.

Table 2. Table of information density.

	Environmental Elements	Attention Percentage	Exposure Percentage	Information Density
Low information density (0, 1]	Crowds	1.5%	7.2%	0.2
	Sky	0.9%	5.1%	0.2
	Tree	0.6%	4.6%	0.2
	Door	0.9%	4.8%	0.2
	Architectural detailing	5.5%	15.4%	0.4
	Road	4.3%	9.8%	0.4
High information density (1, ∞)	Store	11.3%	11.5%	1.2
	Signboards	6.7%	4.1%	1.6
	Architecture	63.1%	37.4%	1.7

As subjects move along the street, their gaze targets also shift, as shown in Figure 8. During the subjects' movement from one end of the street to the other, their gaze points exhibit a clear trend of shifting between different areas of interest over time.

Upon entering the street, the subjects' gaze primarily focuses on the surrounding scenery and historical buildings to form an initial impression of the environment. They may notice historical buildings, cultural heritage, or other significant landmark buildings on both sides of the street, attempting to understand the history and cultural heritage of the area. At this stage, their attention may be relatively broad, not yet focused on specific commercial activities or details. As they continue walking, subjects gradually immerse themselves in the street environment, beginning to observe the surrounding commercial activities and distinctive buildings more closely. They may start fixating on details such as shop signs and window displays, as well as pedestrian and vehicular traffic on the street, to gather more information and enrich their understanding of the area. This progressive refinement of gaze behavior reflects individuals' deeper exploration of the street environment and their more detailed cognition of the surrounding scenery.

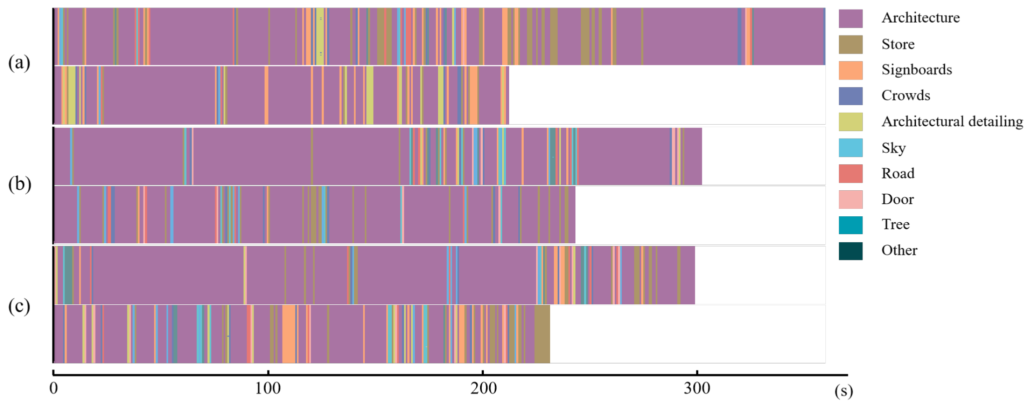

Figure 8. The timeline depicting the fixation of elements, with the horizontal axis representing time in seconds and the vertical axis divided into three categories: (**a**) individuals possessing a deep comprehension of traditional streets; (**b**) individuals with a moderate grasp of traditional streets; (**c**) individuals lacking prior familiarity with traditional streets. Two representative subjects are selected for each category.

Throughout this process, individuals' attention may be influenced by environmental features and shift accordingly, as illustrated in Figure 9. For instance, as they enter bustling commercial areas, they may pay more attention to shop signs and product displays. Conversely, when they stroll into quieter historic districts, they may become more focused on the history and cultural significance of the buildings. Moreover, as subjects pass by specific landmarks or striking buildings, we observe brief pauses and repeated revisits of their gaze points. This pattern reflects the role of these landmarks in guiding visual attention and memory. In the middle section of the street, gaze duration more frequently shifts between shops and historical buildings, indicating the influence of commercial activities on visual attraction. As subjects approach the other end of the street, their gaze tends to concentrate more on individuals, as this area tends to have more functional zones and social interaction points. Overall, we find that the shift in gaze targets is closely related to the subjects' specific positions on the street. Their gaze behavior not only reflects their perception of the environment but also is influenced and guided by the surrounding context. The distribution and duration of these gazes reveal the visual significance of different areas and locations within the street environment.

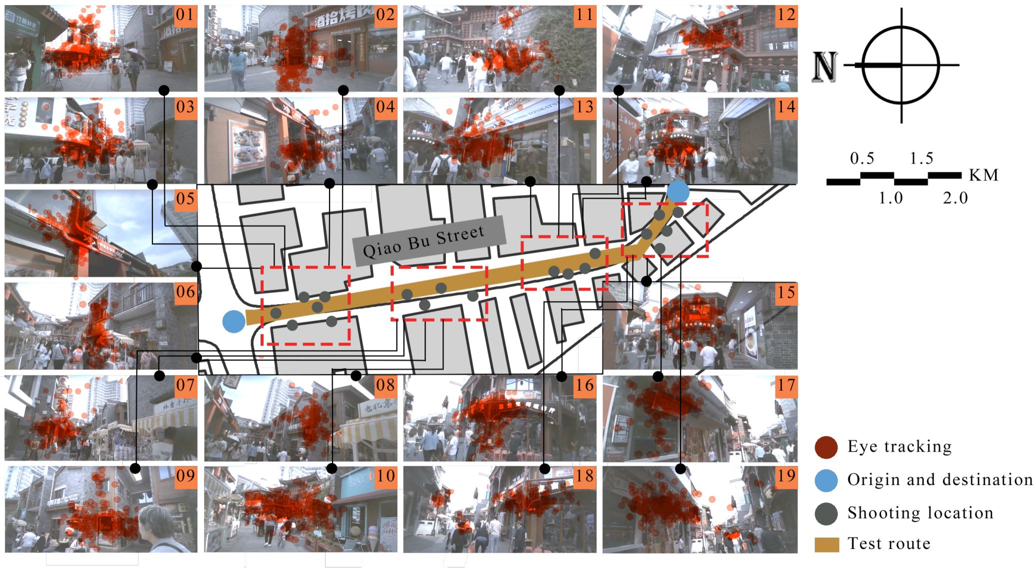

Figure 9. Overlaying a thermal map onto the experimental street section's streetscape.

5. Conclusions

This study conducted a thorough analysis of the visual behaviors of different participant groups in commercialized historic streets and provided unique insights into the streetscape and the attention levels towards various elements. Through descriptions of eye movement patterns and identification of key areas of interest, we revealed the impact of individual knowledge backgrounds and interests on visual attention, offering practical recommendations for urban planning and the commercial development of historical areas.

Firstly, we found significant differences in eye movement patterns among different participant groups. Participants with a background in architecture tended to focus on architectural elements, showing greater interest in architectural details and structures, while individuals with little to no knowledge of architecture were more drawn to commercial activities, displaying a strong interest in commercial elements. This divergence can be attributed to individual levels of knowledge and interests influencing the selection and distribution of visual attention. Those with a background in architecture likely possess knowledge of the area's history, culture, and architecture; hence, they are more inclined to appreciate and focus on architectural elements, including the history, style, and detailed structures of buildings. Conversely, for those with little to no knowledge of architecture, they are more easily attracted to novel commercial activities; thus, they are more likely to focus on commercial elements, such as shops, signs, and pedestrian traffic. This underscores the significant role of individual cognitive backgrounds and interest preferences in shaping visual attention selection and distribution.

Secondly, in analyzing the visual attention differences towards commercialized historic streetscapes, we observed variances in the gaze duration towards various elements among different participant groups. Participants with higher levels of understanding tended to have a higher gaze duration towards architectural elements, while the gaze duration towards commercial elements was most prominent in groups completely unfamiliar with the district. This suggests the need to consider the interests and preferences of different groups when planning and developing commercialized historic streets to enhance their attractiveness and commercial vitality.

Lastly, through the identification of key areas of interest and analysis of fixation durations, we found that participants' gaze behaviors were closely related to their positions on the street and environmental characteristics. As participants progressed along the street, their gaze gradually shifted, reflecting individuals' exploration and cognitive processes of the street environment, which is a dynamic psychological activity influenced by surrounding environments and changes over time and space. This provides important insights for designing more appealing commercialized historic streets.

In conclusion, the findings of this study are of significant importance for understanding the visual appeal of commercialized historic streets and their relationship with individual knowledge backgrounds and interests. However, the study's reliance on a single location and a limited number of participants means that the results may not be widely generalizable. Future research should incorporate multiple historic street locations and a larger, more diverse participant pool to validate and extend these findings. Future research should further explore the impact of different factors on visual behaviors and propose more specific planning recommendations to promote the sustainable development and commercial vitality of urban historical districts.

Additionally, this study also has some limitations, including the small sample size and the lack of consideration for temporal factors such as the time of day and weather conditions, which may affect the results. It is unclear how well informed the participants were about the aim of the study, which may have influenced their behavior and responses. Other sensory experiences, such as sound, interactions with other walkers, and moving traffic, were not accounted for, which could also influence the results.

Future research should further explore the impact of different factors on visual behaviors and propose more specific planning recommendations to promote the sustainable development and commercial vitality of urban historical districts. For instance, weather changes may affect people's walking speed and gaze choices, while tourists may be more inclined to focus on areas related to culture and history. Expanding the research population and including diverse participant types, such as tourists and local residents, will provide a more comprehensive understanding of the visual appeal of commercialized historic streets. Additionally, future studies should consider employing blind study designs to minimize participant bias and incorporate multisensory approaches to offer a holistic understanding of urban environments. By addressing these limitations and incorporating these suggestions, we can more effectively promote the sustainable development of urban historical districts that respect history while encouraging contemporary social and commercial activities.

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