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Risk decision-making behavior in heritage tourism destinations based on eye-tracking experiments in Gulangyu, China

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With the increasing frequency and severity of both natural and man-made disasters, risk decision-making behavior (RDMB) in heritage tourism destinations (HTDs) has gained growing attention. Traditional studies lack a comprehensive quantification from a "human-centered" perspective and ignore individual perceptual differences in earthquake scenarios, particularly in HTDs with complex architectural layouts and diverse road systems. Taking Gulangyu as a case study, this paper integrates behavioral decision theory (BDT) with the Stimulus-Organism-Response (SOR) theory to construct a model for analyzing RDMB. The Santa Barbara Sense of Direction Scale (SBSOD) was employed to assess participants' directional ability, and video stimuli were used to evoke participants' risk perceptions. A Fully Convolutional Network (FCN) was applied to semantically quantify street view images (SVIs), while eye-tracking technology was used to monitor participants' eye movements, physiological responses, and behaviors. Additionally, a multiple linear regression model was utilized to analyze the influence of street view elements (SVEs) on RDMB. The results show that (1) in terms of psychological cognition, individuals with stronger sense of direction exhibited fewer hesitation behaviors and more stable heart rates. (2) regarding physical space, the elements affecting decision-making behavior in street views were ranked as follows: buildings, roads, sky, vegetation, other elements, and signage. (3) in terms of physiological response, participants primarily used buildings and signage to identify their location, followed by vegetation and the sky for environmental observation. Theoretically, this study extends the application of SOR theory and BDT and proposes an analytical path involving psychological cognitive stimulation, physical space quantification, and physiological response (P-P-P). Methodologically, it integrates eye-tracking technology with deep learning (DL) algorithms. Practically, this study provides a basis for improving disaster resilience, enhancing tourist safety perception, and increasing the efficiency of emergency response in HTDs.

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Introduction

Factors such as global climate change, urbanization, and population growth have exacerbated the frequency and severity of natural and human-made disasters (Lee et al., 2016; Zhang and Li, 2022). In 2019, natural disasters claimed approximately 11,000 lives; in 2020, more than 138 million individuals were impacted by natural disasters, resulting in economic losses estimated at 370 billion RMB (Ritchie et al., 2022; Wijkman and Timberlake, 2021). Furthermore, during the same year, 9 heritage sites and 11 World Heritage properties were subjected to 20 natural disaster events, posing significant challenges to the conservation and sustainable management of heritage tourism destinations (HTD) (Li et al., 2023b). The United Nations Sustainable Development Goals (SDG 3 and 11) stress urban safety frameworks to foster inclusive, resilient, and sustainable settlements (Hosagrahar et al., 2016). The Venice Charter (Liang et al., 2023) and International Council on Monuments and Sites (ICOMOS) (Singh, 2010) call for the implementation of effective risk management mechanisms in disaster-prone HTDs. However, heritage sites' unique architecture, complex road systems, and disordered spatial layouts complicate disaster management compared to conventional tourist sites (Amen et al., 2023; Xu et al., 2020). Notably, emergency signage, as an auxiliary facility in disaster management (Hegarty et al., 2005), enhances refuge location recognition (Lynch, 1964; Raubal and Winter, 2002). Research shows that although only 38% of individuals recognize signage, nearly all follow it (Xie et al., 2012). Therefore, analyzing and quantifying risk decision-making behavior (RDMB) in HTD is essential to optimize visual guidance, improve evacuation efficiency, and promote sustainable development.

In the field of tourism, research on disaster management primarily focuses on economic losses (Fuchs and Reichel, 2011; Lavy et al., 2023), disaster mitigation strategies (Kausar et al., 2024; Ritchie and Jiang, 2019), physical and psychological risks (Mızrak et al., 2021; Qiu et al., 2021), and technological applications (Feng et al., 2020; Wachtel et al., 2021). Cui et al. (Cui et al., 2016) analyzed the impacts of natural disasters on tourists' risk perception and the economy. Daly et al. (Daly et al., 2023) proposed disaster risk mitigation strategies like structural reinforcement and community involvement, using the Nepal earthquake as a case study. Trumbo et al. (Trumbo et al., 2016) studied cognitive and emotional responses to disaster risks using a cognitive-affective scale. Chan et al. (Chan et al., 2020), with the Kumamoto earthquake, recommended early warning systems and GIS monitoring to improve post-disaster recovery efficiency. Traditional risk decision-making studies rely on qualitative methods, including surveys (Doi et al., 2015; Mahmud and Aljunid, 2018), cognitive mapping (Montello, 2005), and think-aloud methods (van Elzakker, 2004). With the rise of digital technologies, methods like spatial syntax (Irsyad and Hitoshi, 2022), behavioral mapping (Chen and Cheng, 2020a), two-step moving search (Wang et al., 2024b), and Dijkstra's algorithm (Cao et al., 2021) enable quantitative analysis via spatial topology and behavioral simulation. However, most of the existing methods are limited to macro risk control and lack the study of the micro relationship between spatial layout and individual behavior. Recent advancements in data analysis have fostered human-centered research, delving into behavioral motivations and emotional responses. Compared with studies relying only on self-reported measures or final route outcomes, eye-tracking provides objective evidence of attention allocation during decision-making. This enables a mechanistic analysis of how environmental cues influence route choice. Eye-tracking, a key tool for evaluating tourist experience and perception, has been applied in optimizing visitor experience (Xie et al., 2023), improving advertising effectiveness (Calderón-Fajardo et al., 2024; Chen et al., 2024), managing visitor flow (Wang et al., 2024a), designing exhibitions (Rainoldi et al., 2020), and product development (Yang et al., 2022). In recent years, the role of this technology in risk decision-making research has gradually emerged, e.g., improving navigation systems (Marchiori and Cantoni, 2020; Török et al., 2018), identifying risks (Xie et al., 2024), enhancing safety signage perception (Lai et al., 2024), strengthening disaster prevention and control (Fang et al., 2022; Li et al., 2023a), preserving cultural heritage (Li et al., 2024; Li et al., 2022a), and analyzing the impact of spatial environment on individual wayfinding behavior (Dong et al., 2022; Peebles et al., 2007; Wang et al., 2018). However, current research focuses on disaster mitigation strategies, with limited studies on RDMB in HTD from a human-centered perspective, particularly regarding individual orientation differences, complex environmental impacts, and the lack of quantitative analyses to assess the impact of street view elements (SVEs) on tourists' decision-making in disaster contexts using eye-tracking and image segmentation.

To further analyze RDMB in HTD, this study combines the Santa Barbara Sense of Direction (SBSOD) scale, semantic segmentation of street views, and eye-tracking technology to explore decision-making mechanisms from a human-centered perspective. First, the SBSOD scale controls directional sense variables, establishing the relationship between individual behavior and the environment (Zhang et al., 2023b). Then, semantic segmentation was applied to extract street view visual cues and quantify the impact of the environment on attention distribution (Qiu et al., 2023; Yin et al., 2023). Finally, eye-tracking analysis was used to examine the role of SVEs in guiding attention and optimizing evacuation routes (De la Fuente Suárez, 2020). It should be noted that eye-tracking metrics were used to describe task specific attention allocation and information search, with interpretation bounded by observable behavior and statistical associations. The study contributions include the following. (1) SBSOD was used to control key individual differences, providing a basis for behavioral analyses. (2) The application of the SOR framework and behavioral decision theory was extended to develop an analytical framework linking cognitive stimuli, quantified physical space, and physiological responses. (3) An analysis workflow was proposed that integrates cue quantification, attention allocation analysis, and behavioral outcome comparison. (4) Coordinated optimization recommendations were developed for residents, tourists, site managers, and government agencies to inform emergency evacuation management and spatial improvement in HTD.

Literature review

Mitigation strategies and disaster management for HTDs. Tourism crises refer to events that threaten normal operation, not only affecting tourists' sense of safety and appeal to the destination, but also potentially leading to a decline in the tourism economy and business interruptions (Mair et al., 2016; Sönmez and Allen, 1994). For example, the 1999 Taiwan earthquake (magnitude 7.6) led to a 15% decrease in international tourists (Huang and Min, 2002); the 2011 Great East Japan Earthquake (magnitude 9.0) resulted in a 27.8% decrease in international inbound tourists (Abe and Potroz, 2021); and the 2015 Nepal earthquake (magnitude 7.8) caused nearly 9000 deaths, the destruction of hundreds of heritage sites, and $6.3 billion in tourism losses, 45.6% of total losses (Sharma and Tham, 2021). To address the impact of disasters on tourism, various disaster reduction strategies have been proposed. Choi et al. (Choi et al., 2023) analyzed tourists' disaster response behaviors during earthquakes using questionnaires and logistic regression, proposing disaster education, optimized shelter configurations, and improved information dissemination. Ma et al. (Ma et al., 2020) suggested strategies like pre-disaster preparedness, emergency response, and image restoration to enhance tourists' risk perception. Amelia et al. (Amelia et al., 2024), integrating GIS with multi-risk assessments, proposed safety planning and community resilience strategies based on risk maps. While pre-disaster planning is essential for disaster management (Santana, 2004), the 2011 Great East Japan Earthquake showed the significant impact of inadequate evacuation guidance on evacuation efficiency and safety (Makinoshima et al., 2021). Therefore, it is crucial to optimize evacuation path design and guidance. Nahum et al. (Nahum et al., 2020) used beacon navigation to improve evacuation routes and enhance evacuation efficiency. Mohammed et al. (Mohammed et al., 2023) identified congestion areas through pedestrian simulations and proposed suggestions for optimizing channels, adding signs, adjusting exits, and diverting evacuation flows. However, existing research has shortcomings in areas such as tourists' risk perception (Cioccio and Michael, 2007), evacuation planning (Wang and Ritchie, 2012), risk perception assessment (Matyas et al., 2011; Xie et al., 2021), and disaster management methods (Blackman et al., 2011; Hall et al., 2019; Urbina and Wolshon, 2003), lacking a "human-centered" approach to RDMB in HTD.

RDMB based on psychological and cognitive processes. In RDMB, differences in sense of direction directly affect wayfinding efficiency (Castelli et al., 2008; Verghote et al., 2019). The SBSOD scale, proposed by Hegarty in 2002, is widely validated as an effective tool for assessing spatial orientation ability (Davies et al., 2017; Hegarty et al., 2002; Meneghetti et al., 2014). Studies show that individuals with a higher sense of direction scores perform better in wayfinding speed, accuracy (Kozhevnikov and Hegarty, 2001), backtracking behavior (BTB) (Kato and Takeuchi, 2003), and strategy application (Jamshidi et al., 2020). Lin and Wang (Lin and Wang, 2011) found that individuals with a stronger sense of direction respond faster and experience lower cognitive load when using electronic maps. Koletsis (Koletsis et al., 2017), using Tobii Pro Glasses hardware, observed that users with weaker spatial abilities tend to overlook environmental cues and prefer small-scale landmark-based navigation. Tahir (Tahir and Krogstie, 2023) noted a negative correlation between weaker spatial ability and Perceived cognitive load and hesitant behavior. Ishikawa T (Ishikawa and Zhou, 2020) found that individuals with a weaker sense of direction struggle to significantly improve orientation ability through training. The SBSOD scale improves experimental accuracy, provides theoretical support for efficient wayfinding system design, thus serving as a basis for personalized training and route guidance, and enhancing disaster emergency response capabilities (Shamsuddin and Din, 2016). However, existing research has limitations: (1) the applicability of the scale in complex environments, such as HTD, remains inadequately verified; (2) there is insufficient empirical support for interventions addressing spatial ability differences; and (3) inadequate integration of risk decision-making and cognitive behavior theories.

RDMB on physical space. In The Image of the City, Kevin Lynch proposed five elements of urban design: paths, edges, districts, nodes, and landmarks (Anagnostopoulos et al., 2017), forming the basic structure of urban space (Manghi and Denis, 2003) and reflecting human cognition of space (Siegel and White, 1975). Traditional environmental perception research relies on methods including questionnaires, interviews, and field observations (Brancato et al., 2022; Chen and Cheng, 2020b; Ji et al., 2021). However, with the development of deep learning (DL) and big data technologies, image segmentation has significantly improved analysis efficiency (Zhang et al., 2023a). Raubal (Raubal and Winter, 2002), based on Sorrows and Hirtle's framework, proposed a landmark salience model, suggesting that visual, semantic, and structural factors are the main determinants of landmark use. Fan (Fan et al., 2023) analyzed SVIs using computer vision models to reveal the correlation between urban visual characteristics and community socio-economic conditions, indicating that urban features predict indicators like travel behavior, poverty, crime rates, and health. Wu (Wu et al., 2024), combining Baidu SVI, DL, and spatial syntax, analyzed different population groups' perceptions of urban street resilience and street accessibility, proposed a framework for integrating resilience perception into street planning. Image segmentation and DL extracts spatial elements from SVIs, supporting the quantification of urban design elements, enhancing analysis efficiency, and reducing human intervention. These provide a data foundation for RDMB, evacuation paths, and shelter planning, aiding governments and communities in formulating precise disaster emergency plans and enhancing safety in heritage sites. However, current research faces limitations in integrating traditional methods with modern technologies, perception with street planning, and applying image segmentation and DL.

RDMB based on physiological characteristics. Technological advances provide new perspectives on human-computer interaction, with eye-tracking considered a window into internal cognitive processes (Rayner, 1998). Delikostidis (Delikostidis, 2011) employed a mobile eye-tracking approach, coupled with audible thought, to assess the usability of a real-world mobile navigation system. Liao (Liao et al., 2022c) investigated participants' map-matching strategies using a mobile eye-tracker, focusing on higher cognitive processes related to spatial orientation and self-localization during wayfinding. Zhou et al. (Zhou et al., 2020) studied gender differences in map navigation performance under time pressure in a real indoor subway environment. Liao (Liao et al., 2019) leveraged DL to infer user tasks from eye-tracking data during pedestrian navigation. Yu (Yu et al., 2023) used eye-tracking to simulate subway station wayfinding and found differences in behavior under varying pressure levels. In the context of RDMB, Ding (Ding, 2020) and Chen (Chen et al., 2020) used wearable eye-tracking devices to assess evacuation sign design effectiveness and proposed optimization strategies for sign placement, color, graphics, and flashing. Zhao (Zhao et al., 2020) utilized GPS and eye-tracking devices to investigate tourists' interactions with signage systems during wayfinding in public spaces, analyzing the correlation between visual attention and wayfinding efficiency. Eye-tracking experiments provide evidence for the development of evacuation strategies aligned with human cognitive mechanisms and instinctive responses by capturing dynamic behaviors during evacuation and revealing attention allocation, information processing, and decision-making processes, thus reflecting cognitive states and behavioral intentions in RDMB (Bednarik et al., 2012; Duchowski and Duchowski, 2017; Opach and Nossum, 2011). However, existing research has limitations in understanding cognitive processes, differences in pressure and task contexts, and effectively integrating eye-tracking data with other behavioral data.

RDMB analysis based on svis and eye-tracking. With the development of eye-tracking and image segmentation techniques, spatial elements in SVIs are accurately extracted, revealing the influence of the urban environment on individual behavior and risk decision-making, providing new research perspectives for urban perception, safety assessment, and emergency management. For example, Liao (Liao et al., 2022b) used eye-tracking data to infer users' spatial familiarity with urban environments, applying DL methods to analyze key eye-tracking features that influence spatial familiarity judgments. Yao (Yao et al., 2019) constructed a human-computer adversarial scoring framework, combining DL and iterative feedback to quickly and efficiently assess urban perception. Naik et al. (Naik et al., 2016) proposed a computer vision algorithm to measure the perceived safety of street views. Gou A (Gou et al., 2022a) used neural networks to analyze the green view index and its influencing factors on streets in Jing'an District, Shanghai, providing scientific evidence for human-centered planning and street green space renovation. The combination of eye-tracking and image segmentation technologies enables precise extraction of spatial elements from street views, analyzing individual attention allocation and RDMB in disaster scenarios. From the perspectives of both visual and spatial environments, this approach provides data support for urban perception (Karim, 2023), interface optimization (Dörner et al., 2024), safety monitoring (Wu et al., 2022a), and emergency evacuation (Huang et al., 2021), supporting governments and communities in optimizing evacuation routes, shelter layouts, and enhance public safety. However, existing research lacks sufficient validation in complex scenarios such as HTD and disaster emergencies, while failing to integrate these technologies with cognitive behavior theories and psychological models, overlooking the impact of situational factors such as stress and anxiety on RDMB.

In summary, although existing research has made progress in applying eye-tracking, image segmentation, and DL technologies to risk decision-making, there are still shortcomings regarding theoretical frameworks, technology integration, and practical applications. This is especially true for "human-centered" risk decision-making research in HTD, where the "psychological-physical-physiological" factors have not been fully considered.

Theoretical framework

Kevin Lynch's five elements of spatial organization laid the foundation for wayfinding behavior research, emphasizing the role of environmental elements in cognition and path selection. Based on this, Arthur and Passini (Arthur and Passini, 1992) proposed treating signage, maps, textual descriptions, architecture, and urban spaces as wayfinding information, dividing the process into three stages: information processing, decision-making, and decision execution. However, wayfinding processes are not entirely rational. Simon (Simon, 1955), through behavioral decision theory (BDT), revealed the influence of cognitive biases, emotions, and environmental factors on decision-making. Wang (Wang et al., 2016) applied BDT to analyze commuters' behavior and risk preferences in path selection, explaining decision-making under time pressure and safety concerns. Unlike the application of theories such as the theory of planned behavior (TPB) (Tan et al., 2022; Zaremohzzabieh et al., 2021), game theory (Ibrahim et al., 2019; Zheng and Cheng, 2011), and protection motivation theory (Kurata et al., 2023) in emergency evacuation research, BDT focuses on explaining bounded rationality during evacuation, revealing the roles of psychological, physical, and physiological factors in decision-making. Although BDT can effectively explain cognitive biases and emotional factors in individual decision-making, there is no systematic research framework for the behavioral decision-making process in emergency evacuation scenarios.

The Stimulus-Organism-Response (SOR) model was first proposed by Woodworth (Woodworth, 1918) to explain how external stimuli trigger different responses through an individual's internal state. Mehrabian and Russell (Mehrabian and Russell, 1974) extended this theory based on environmental psychology, exploring the impact of environmental stimuli (S) on an individual's (O) emotions and cognition, which drive behavioral response (R), emphasizing the influence of the environment on human emotions and behavior. Pahrudin (Pahrudin et al., 2023) applied the SOR model to analyze the impact of disaster information on tourists' emotions and cognition, subsequently altering their evacuation behavior. Li (Li et al., 2021a) found, through the SOR model, that the stimulus of the pandemic environment affects individuals' emotions, thereby influencing their purchasing behavior. In tourism decision-making behavior research, environmental changes and emotional fluctuations act as stimuli, with tourists as the organism, and responses including changes in evacuation and purchasing behavior. Thus, the SOR framework effectively reflects the impact of environmental changes on tourists' behavior.

The TPB explains the formation of behavioral intentions, and the SOR theory gives a theoretical framework for environmental stimuli to influence behaviors through emotion and cognition, and the combination of both helps to comprehensively understand the behavioral process of RDMB. This study, based on the BDT and the SOR framework, combines the SBSOD scale, scenario simulation, eye-tracking experiments, semantic segmentation technology, and DL algorithms to construct an analytical pathway of P-P-P, exploring individuals' risk perception and path selection during earthquake emergency evacuation. Specifically, the stimulus (S) induces emotional responses through video simulations; the organism (O) uses semantic segmentation to extract spatial elements from SVIs and assesses the impact of environmental factors on attention distribution; the response (R) is monitored through eye-tracking technology to capture physiological, eye-tracking, and behavioral responses, revealing the risk perception and decision-making process (Fig. 1). This framework provides

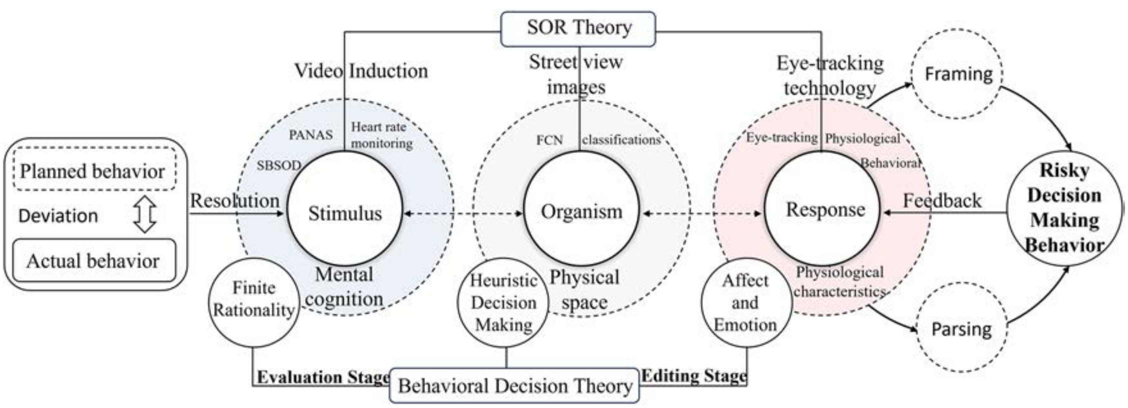


Fig. 1 Theoretical framework.

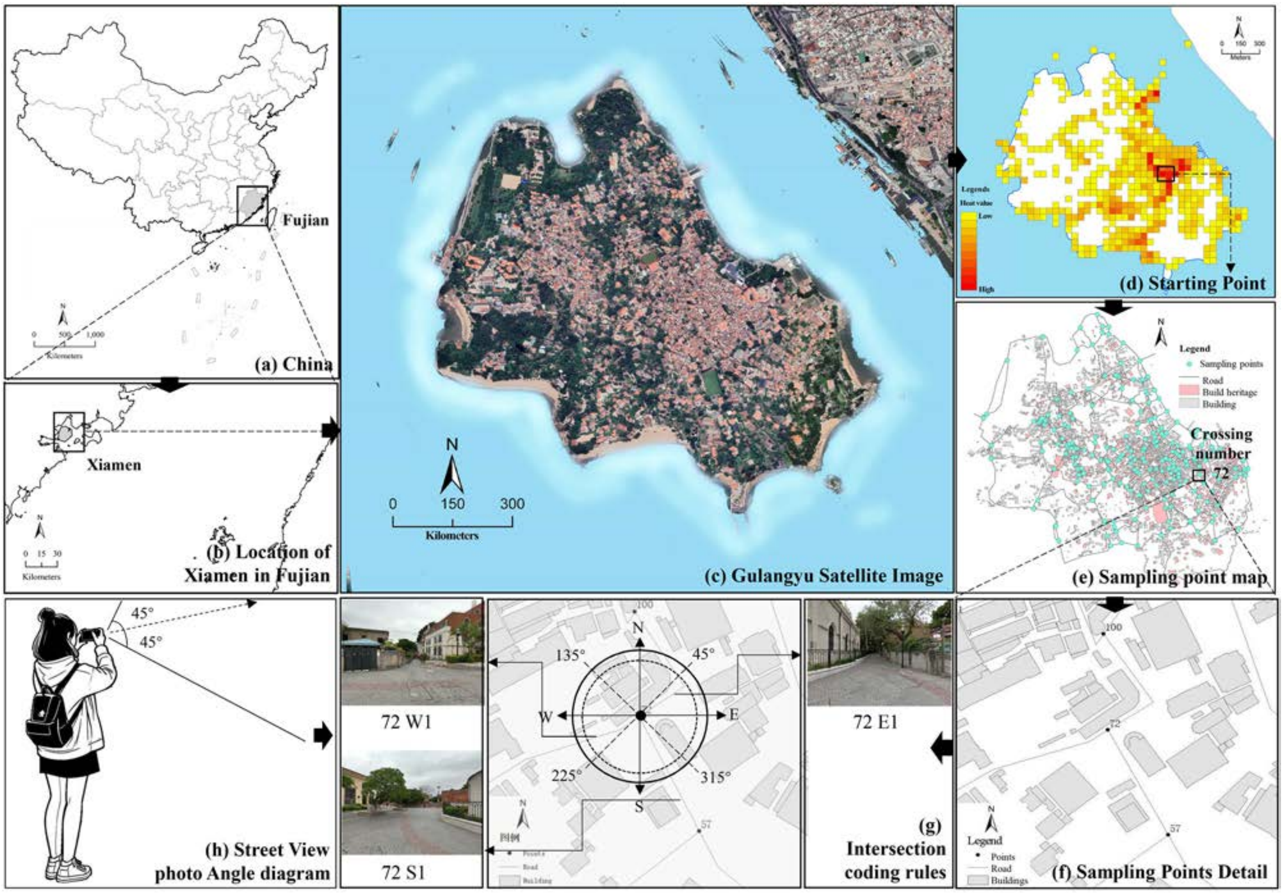


Fig. 2 Study area and street-view sampling framework in Gulangyu. **a** Location of the study area in China; **b** Location of Xiamen in Fujian; **c** Satellite image of Gulangyu; **d** Distribution of starting points; **e** Sampling point distribution; **f** Sampling point details; **g** Intersection coding rules; **h** Street-view photo angle diagram.

technical support and scientific evidence for optimizing environmental design, alleviating evacuation anxiety, and developing precise evacuation plans to enhance public safety.

Materials and methods

Study area. Gulangyu (N24°26'51", E118°3'43") is located in Xiamen, Fujian Province, with an area of 1.88 square kilometers. Known as the *Museum of International Architecture*, Gulangyu was listed as a UNESCO World Heritage site in 2017 for its "Historic International Settlement" status, attracting a large number of domestic and international tourists (Li et al., 2021b; Li et al., 2023c), as shown in Fig. 2. Due to its island topography, most of Gulangyu's streets were formed before the 1930s, presenting a narrow, winding layout designed primarily for pedestrians. This not only increases the difficulty of evacuating tourists but also heightens the risk of tourists getting lost due to old buildings and an uneven signage system. Every year, tourists seek help due to getting lost (Li et al., 2017; Li Yuan et al., 2017; Shi et al., 2023). Moreover, the vulnerability of Gulangyu's historical buildings and its unique geographical location expose it to higher risks during disasters. Under disaster conditions, once transportation is disrupted, anxiety and the difficulty of seeking shelter will significantly increase. These characteristics make Gulangyu an exemplary case for studying emergency evacuation and risk management. Its rich historical buildings and high tourist traffic provide a typical background. The complex street layout and inadequate signage system highlight the necessity of improving evacuation efficiency. Its special geographical location and transportation modes offer real-world scenarios for studying RDMB. Finally, its high-risk characteristics and cultural heritage value provide a universal framework and practical reference for research on risk management and tourist safety strategies.

Research framework. The procedure follows three steps (Fig. 3): (1) Data input: The emergency evacuation routes at heritage sites adhere to a "point-line-plane" linking method. Through onsite signage and route surveys, simulating the perspective of evacuees, data points are established at all island intersections to form evacuation routes. (2) Experimental stage: Begins with the evaluation of participants' sense of direction utilizing SBSOD. Participants are introduced to the experimental scenario, where their RDMB is observed via eye-tracking devices within a risk decision-making platform. Based on this, the proportion of street elements is quantified through image segmentation techniques to investigate the impact of streetscape elements on RDMB. (3) Data Output: The ordinary least squares (OLS) linear regression model analyzes the correlation between the semantics of photographs and eye-tracking data to identify key factors influencing RDMB at HTD. Subsequently, based on these insights, recommendations for the optimization of emergency signage are proposed.

Data sources. Photographs of intersections across Gulangyu served as the primary data source. It can help desktop eye-tracking technology circumvent equipment and technical problems (e.g., battery life, inaccurate GPS positioning, etc.), complex environmental factors (e.g., traffic, weather, light, and noise, etc.), and individual differences (e.g., walking speed, herd mentality, etc.), that may occur in real-world environments (FRANCIONI

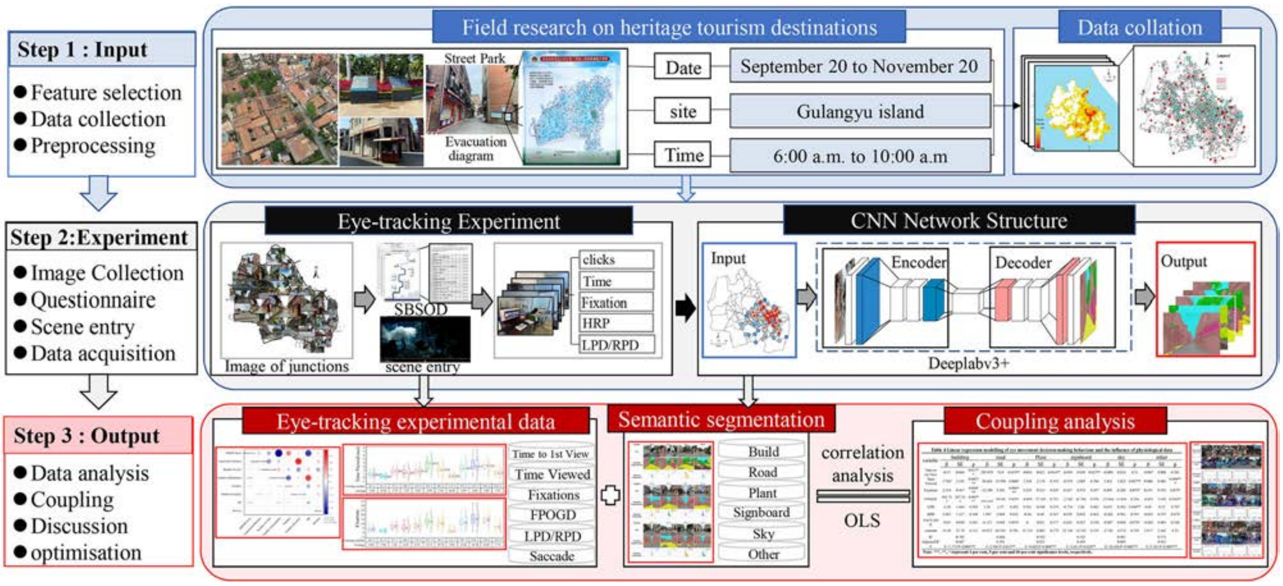


Fig. 3 Research framework.

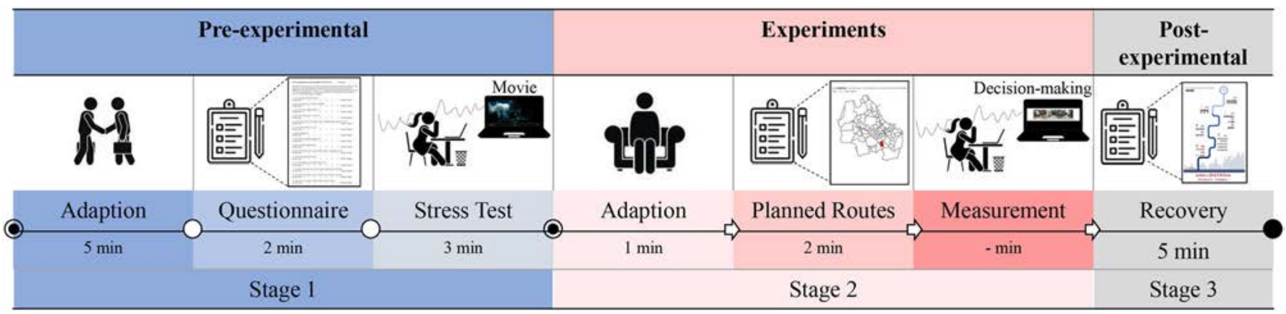


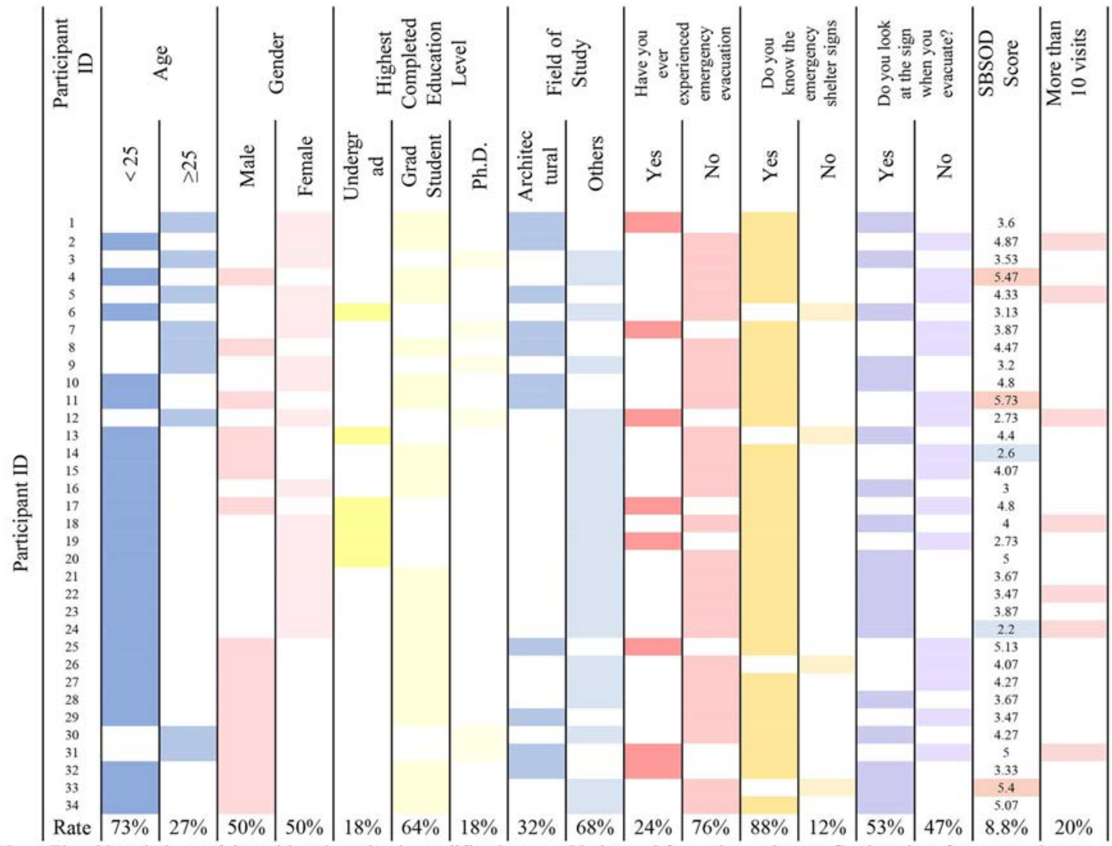
Fig. 4 Experimental flow chart.

and LENZERINI, 2008; Yu et al., 2018). To control the herd mentality in RDMB, image collection occurred between 6 am and 10 am from 20 September to 20 November 2023, ensuring that the captured images were free from human elements and interference. A total of 107 junction nodes and 500 sampling points were collected through 9 rounds of research. All photographs were taken using a lens with a focal length of 24 mm, with the collection height controlled at 1.6 m. A total of 1326 images were collected (Zhu et al., 2020), as shown in Fig. 2h. On this basis, 804 images devoid of human elements were selected as the initial dataset. Analyzing the heatmap of pedestrian streamlines on Gulangyu, the street park with the highest foot traffic was chosen as the starting point (SP), and all the evacuation routes were mapped, as depicted in Fig. 2d. After simulating the field routes, the images were numbered (Fig. 2g). Meanwhile, the numbering of the intersections and evacuation routes was carried out on the GIS platform. The platform for RDMB selection of Gulangyu intersection photographs was created based on the connection between the numbers above, and RDMB of participants was observed through the selection.

Experimental design and procedure

Participants. To ensure the reliability of experimental results, this study selected college students with comparable cognitive levels as participants, enrolling only adults aged 18 and above with full informed consent capacity. During the pre-experimental phase, 10 participants were recruited to evaluate equipment stability, data accuracy, and procedural feasibility. The formal experimental phase involved 40 participants (19 females, 21 males) with an average age of 24 years (SD = 2.36), representing academic backgrounds in geography, psychology, engineering, arts, and management. After data screening, 6 cases were excluded as invalid, including 2 participants with incomplete records due to task interruption, 3 participants with missing physiological data due to signal loss, and 1 participant with invalid data due to calibration failure. The final valid sample comprised 34 participants with balanced gender distribution, all possessing normal or corrected-to-normal vision.

Equipment. The experiment used a Gazepoint GP3 HD non-invasive desktop eye tracker to collect data at a sampling rate of 60 Hz. The experimental stimuli were presented on two 19.45-inch monitors with a screen resolution of 1920 × 1080 pixels, and the recording accuracy of the eye tracker was 0.5°. Recorded variables included gaze location and gaze pattern measures, and concurrently captured fixation behavior, click counts, heart rate, electrodermal activity, and pupil related measures (Table 2). These data were used to compute the area of interest based on gaze metrics and to analyse the route choice process. Eye-tracking and associated physiological measures characterized attention allocation and information search during the task and were analysed in relation to click behavior. Interpretation was limited to gaze distribution and choice behavior during the task, and the measures were not used as direct evidence of participants' cognitive states or emotional conditions.



Note: The abbreviations of the subjects' academic qualifications are Undergrad for undergraduates, Grad student for postgraduates.

Fig. 5 Participants' basic personal information.

Procedure. The experiment comprised three stages (Fig. 4). In Stage 1, participants received an explanation of the study purpose, procedures, and precautions, including foreseeable risks, and provided written informed consent. Participants were informed that a non-invasive desktop eye tracker would collect visual data for subsequent area of interest (AOI) metric analysis and visualization. The study was assessed as minimal risk, with possible transient eye fatigue or mild discomfort, and the earthquake video may induce emotional fluctuation. Participants could pause, rest, or withdraw at any time without adverse consequences. No direct personal benefit was promised. The anticipated benefit was to provide verifiable evidence to support evacuation organization, wayfinding optimization, and emergency management in HTDs. Participants then completed a questionnaire on basic characteristics and sense of direction, and watched a 3-minute earthquake video to establish the risk scenario.

Stage 2 consisted of a desktop eye tracking task. Before the task, seating posture and viewing distance were adjusted, and a five point calibration was conducted to ensure tracking accuracy. The task included two parts. First, after being informed of the evacuation start point and the shelter destination on the Gulangyu map, participants drew a planned escape route on the map to record route planning preferences. Participants then proceeded to a route choice interface that presented SVIs of multiple intersections together with preset route options. Based on the information identified from the images, participants selected routes by clicking to simulate the evacuation process until reaching the shelter. Task duration varied with individual response speed. Eye tracking data and click behavior were recorded concurrently during the task.

Stage 3 was a post task questionnaire used to collect participants' evaluations of the experimental process and feedback.

Data processing. Data processing and metric computation took place after the experiment. Eye-tracking and associated physiological data were managed in a coded and de-identified manner and stored on an encrypted, access controlled drive, with access restricted to authorized research team members. Results were reported only in anonymized or aggregated form. The data will be retained for five years after study completion and then securely deleted. Names were stored separately from the eye tracking dataset. The analytical dataset contained no names and was linked to name information only via coded identifiers. The code to name the linkage file was encrypted and access was limited to the minimum necessary personnel.

Recording quality was checked by verifying calibration validity and identifying tracking interruptions. AOIs were then defined based on the task interface and street view content using consistent criteria across participants and intersections. After AOI definition, gaze point and gaze event data were exported using the Gazepoint analysis software, and gaze heatmaps and gaze plots were generated from de-identified records. The data were then cleaned according to predefined rules by processing or excluding blinks, brief signal loss, and obvious noise. Core AOI metrics were computed, including total fixation duration, fixation count, time to first fixation, and revisit count, and summary tables were exported for statistical analysis.

Methods. The majority of the sample population comprised students, with 50% undergraduates, 64% postgraduates, and 18% PhD students. Architecture majors accounted for 32%, while students from other disciplines comprised 68%. Questionnaire data revealed that while 76% of participants had not undergone emergency evacuation drills, 88% were familiar with emergency shelter signs (Fig. 5). During disasters, over half (53%) of the

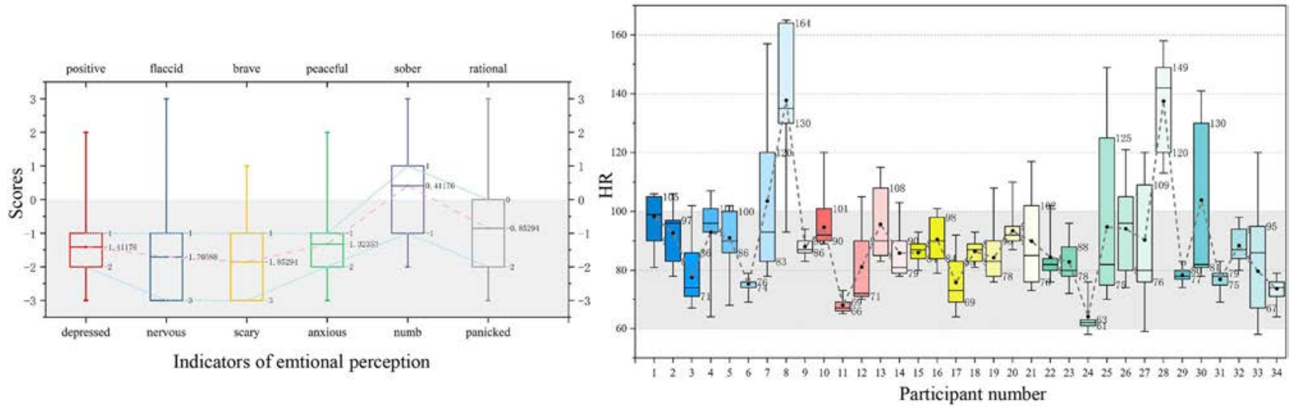


Fig. 6 Psychological and physiological values after video viewing.

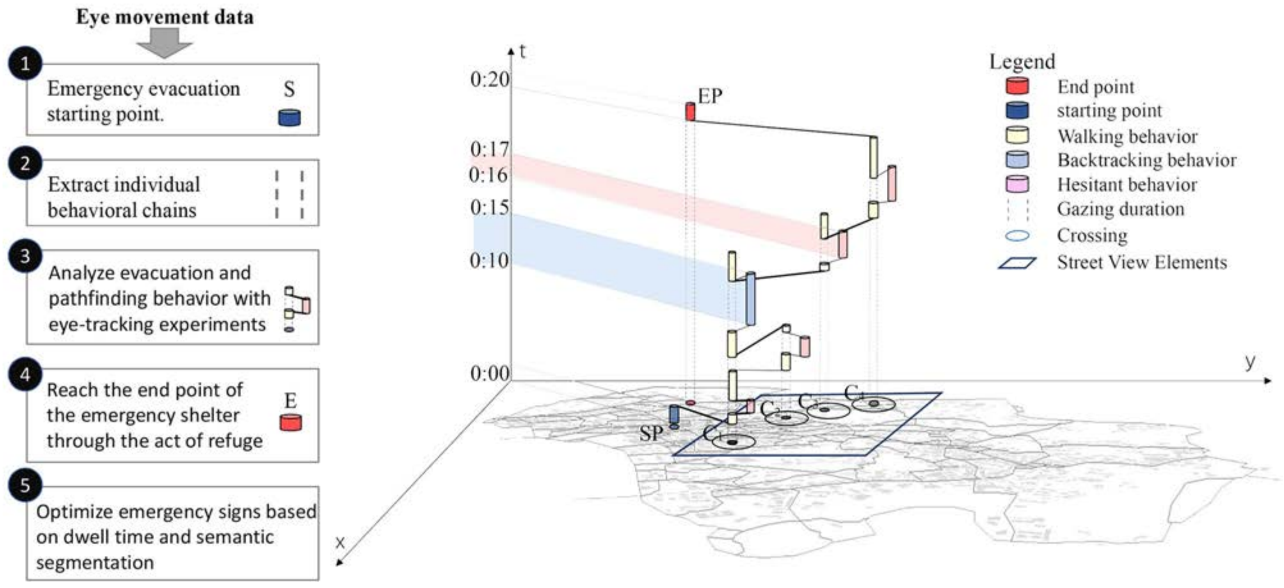


Fig. 7 Time series diagram.

participants tended to adhere to predetermined emergency evacuation routes. Participants exhibited significant individual differences in environmental perception and RDMB.

Psychological and cognitive stimuli data processing. To control for experimental variables, individual spatial abilities were evaluated using SBSOD, a self-report instrument (Dunn and D'Amelio, 2020). Most participants scored close to the mean SBSOD scale was 4.04 (SD = 0.89). Participants P4, P11 and P33 exhibited excellent spatial ability, with scores exceeding 5.4; whereas participants P14 and P24 demonstrated weaker spatial abilities, scoring below 2.81. It means that the participants were selected to have an intermediate to a high level of sense of direction, which is possibly conducive to the accurate perception and understanding of the environmental features of HTD.

Based on the P-P-P framework, this study induced participants' emotional responses by playing earthquake-related videos (Fernández-Aguilar et al., 2019). After watching the video, participants filled out the Positive and Negative Affect Schedule (PANAS). The results showed that most participants reported feelings of depression, tension, fear, and panic (Fig. 6a). Meanwhile, physiological monitoring revealed that 65% of participants had a peak heart rate exceeding 100 beats per minute (BPM) after watching the video (Fig. 6b). This indicates that video stimuli can effectively induce emotional responses, providing simulation conditions for an emergency evacuation scenario at both the psychological and physiological levels.

Through the difference between planned and actual behaviors in RDMBs, combining the spatial "five elements", integrating spatiotemporal sequences and eye-tracking data, we construct a series of escape trajectories composed of geotags ($p = [p]$), forming a spatiotemporal sequence $S = <(x_0, y_0, t_0), \ldots, (x_n, y_n, t_n)$, where (x, y) represents the coordinates of the visual gaze point and t is the time point (Fig. 7). By the analysis of walking, BTB, and hesitation behaviors (HB) in the chain of RDMB, this study uses BTB to reflect the temporal stagnation and potential cognitive conflicts in the escape process of the participants, and reveals the role of environmental structure and cognitive abilities in RDMB (Bahmani et al., 2023).

Physical space quantification data processing. Based on the P-P-P framework, this study employs the DeepLabv3+ semantic segmentation algorithm, which is based on the Fully Convolutional Networks (FCN) architecture (Gou et al., 2022b), to quickly identify environmental factors related to risk decision-making in SVIs. This algorithm integrates the Xception backbone network into the traditional Convolutional Neural Network (CNN) and introduces an encoder-decoder structure, thereby improving the accuracy and processing efficiency of image edge segmentation (Chen et al., 2017). Test results on the ADE20K scene semantic annotation dataset indicate that DeepLabv3+ can segment images into 151 categories, achieving an average recognition accuracy of 77.21% (Tsang, 2019). Using this algorithm, the study performs semantic segmentation on the collected SVI, categorizing the identified visual elements into two main categories and six subcategories (Table 1), to systematically explore the environmental visual factors influencing RDMB in HTD (Xu et al., 2022).

Physiological response data processing. Eye tracking is used to characterize visual information acquisition and attention allocation during the earthquake scenario video and intersection choice tasks (Dong et al., 2020; Kiefer et al., 2017; Yarbus, 2013; Ye et al., 2022). Based on the S–O–R framework, response measures are grouped into three categories, namely eye tracking metrics, physiological measures, and behavioral indicators (Table 2). Eye tracking outputs include time stamped gaze samples, fixation and saccade events, and pupil diameter. In this study, AOI based metrics are used to quantify time to first attention, dwell time, and fixation count, and saccade magnitude(SACCADE_MAG) is used to describe visual search demand. In addition, click counts at intersections are treated as observable choice outcomes to support the interpretation of route selection differences. Prior to analysis, records are screened and subjected to quality control. Participant information is managed using coded identifiers to reduce privacy risk.

Ordinary least squares linear regression model. To investigate the mechanism of influence between elements in SVIs and RDMB (Gou et al., 2022b), OLS is employed to analyze the correlation between the pixel elements of SVIs and eye-tracking experiment data to determine factors that significantly impact RDMB (Armougum et al., 2019). The expression for this model is as follows:

$$y_i = \beta_0 + x_i\beta + \varepsilon_i\,(\mathrm{i} = 1,\ 2,\ \ldots,\ \mathrm{n}) \tag{1}$$

where: y_i represents elements within SVI; x_i signifies the independent variable, which indicates eye-tracking indices in SVI; ε_i denotes the error term; β represents the coefficient of the independent variable, and β_0 represents the intercept. The magnitude of the coefficient indicates the degree of influence of the factor (Han et al., 2020).

Table 1 Division of objects of interest.

Indicator Category	Object of Interest	Classes
Immovable Cultural Heritage	Road	Road, Sidewalk, Floor, Stairway, Stairs, Path
	Building	Building, Wall
	Sky	Sky
Modifiable Facilities	Plant	Tree, Palm, Grass, Plant
	Signboard	Signboard, Poster
	Other streetscape elements (OSE)	Streetlight, Awning, Light, Railing, Bannister

Results

The experimental results indicate that the average time for participants to complete RDMB was 448 seconds (SD = 290 s), with the time range from 47 s to 1061 s. Through spatiotemporal sequence data analysis, the difference between the planned evacuation route (Fig. 8a, behavioral intention) and actual behavior (Fig. 8b, executed behavior) showed that 88.24% of participants' planned routes were consistent with the shortest path, and the more frequently participants visited Gulangyu, the higher the consistency between their planned route and actual behavior. However, 79.41% of participants deviated from the planned route during the experiment (Fig. 8c). The study further selected 37 SVIs from 12 intersections with more than two return trips, and analyzed the reasons for deviation from the P-P-P perspectives.

Analysis of psychological and cognitive stimuli. From the perspective of psychological cognitive stimulation, this study analyzes RDMB in HTD using the individual sense of direction. Hegarty (Hegarty et al., 2002) proposed that the sense of direction is directly related to wayfinding behavior, but experimental data indicate that the behavioral patterns in heritage sites differ significantly from those in urban environments (Fig. 9). Experimental analysis shows a significant negative correlation (−0.562) between the frequency of visits to Gulangyu and task completion time, suggesting that participants who are more familiar with the area are able to find emergency shelters more quickly. Moreover, the duration of the experiment is positively correlated (0.845) with the number of round trips, but negatively correlated (−0.571) with visit frequency, reflecting the complexity of navigation decisions in unfamiliar environments. Additionally, the positive correlation (0.698) between hesitation frequency and heart rate further validates the effectiveness of the experimental design. More specific analysis reveals a significant negative correlation between sense of direction and hesitation frequency

Table 2 List of eye-tracking physiological behavioral data in RDMB.

Indicator Category	Indicator Name	Interpretive construct	Task phase
Eye-tracking indicators	Time to 1st View (Li et al., 2022b)	First attention	Early decision phase
	Time Viewed (Tsai et al., 2012)	Sustained attention	Target detection and information search
	Fixations (A et al., 1980)	Visual search demand cue	Discrimination, identification, and information search
	FPOGD (Fixation Point of Gaze Duration) (Destyanto and Lin, 2023)	Fixation dwelling intensity cue	Fixation on key cues
Physiological indicators	LPD/ RPD (left eye pupil/ right eye pupil) (Liao et al., 2022a)	Arousal cue	Response changes during scenario induction and task execution
	Saccade Magnitude (Wu et al., 2022b)	Visual search span cue	Visual search
	Heart rate pulse (HRP)	Physiological activation cue	Overall response changes during task execution
	Galvanic skin response (GSR)(Alvarsson et al., 2010)	Stress and arousal cue	Response changes before and after scenario induction or across conditions
Behavioral indicators (BI)	Average Clicks (Buscher et al., 2010)	Choice outcome	Intersection choice
	Hesitant behavior	Uncertainty cue	Decision stalling
	Backtracking behavior (BTB)	Error correction cue	Deviation and correction

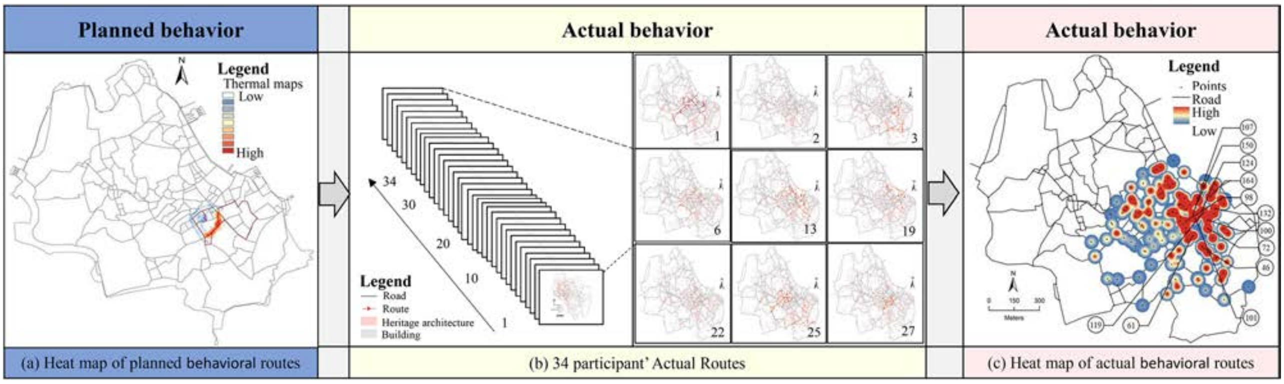


Fig. 8 Planned and actual behavioral routes in the evacuation experiment. a Heat map of planned behavioral routes. **b** Actual routes of 34 participants. **c** Heat map of actual behavioral routes.

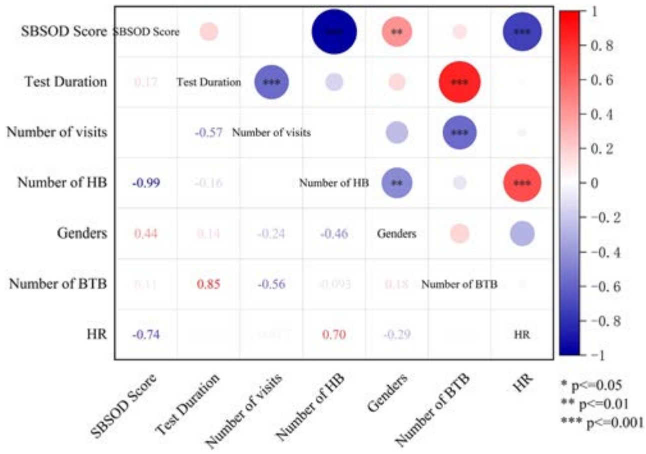


Fig. 9 Heat map of correlation between direction sense and decision behavior.

(−0.988) and heart rate (−0.737), indicating that individuals with a stronger sense of direction tend to hesitate less and have lower heart rates. Furthermore, the sense of direction is positively correlated (0.439) with gender, suggesting that males generally have a better sense of direction than females.

Analysis of physical space quantification. Through semantic segmentation of 37 SVIs from 12 intersections, this study analyzes the distribution of five types of environmental elements (Fig. 10). The results show that architectural elements account for 54.19%, and road elements for 25.49%, with a click-through rate of 64%, indicating their significance in decision-making. Sky, vegetation, and public facilities account for 9.97%, 9.62%, and 0.43%, respectively, while signage elements, although constituting only 0.29%, have a click-through rate of 23.67%.

The results suggest that architectural and road elements play a key role in risk decision-making in streetscapes where individuals are prone to getting lost, particularly in HTD. Additionally, participants are more likely to click on street views containing signage, highlighting the importance of proper signage elements.

Analysis of physiological response. Through the analysis of intersections where individuals are prone to getting lost, this study explores street view characteristics from both eye-tracking indicators and bioelectrical indicators. From the eye-tracking data (Fig. 11a), the ranking of elements by average time to 1st view is as follows: other (156.44 s), signage (150.43 s), sky (139.64 s), plants (138.74 s), road (137.62 s), and building (131.53 s). the ranking by total fixation duration is: building (14.23 s), signage (7.28 s), sky (3.06 s), plants (3.04 s), road (3.00 s), and other (2.54 s). The ranking by fixation count is: building (62.3 times), signage (33.1 times), sky (14.56 times), plants (13.83 times), road (13.56 times), and other (9.67 times). The ranking by Fixation Point of Gaze Duration (FPOGD) is: building (0.29 s), signage (0.29 s), other (0.29 s), road (0.28 s), sky (0.27 s), and plants (0.25 s).

From these rankings, it can be inferred that in RDMB, individuals first use buildings and signage to determine their location, then observe the environment based on other elements such as plants and sky, with the last elements being others and roads. From the bioelectrical data (Fig. 11b), the ranking of SVEs by their impact on pupil size is: sky (21.18px), other (21.09px), building (20.98px), road (20.87px), signage (20.84px), and plants (20.69px). The ranking by impact on SACCADE_MAG is: sky (315.30px), other (295.90px), plants (293.23px), signage (268.12px), building (260.67px), and road (255.64px). The ranking by impact on heart rate variability is: other (259.28), building (197.72), sky (180.09), signage (168.07), road (163.59), and plants (163.57). The ranking by the impact on Galvanic Skin Response (GSR) is: plants (1,191,288.06ω), other (1,159,451.77ω), sky (1,077,194.19ω), road (1,076,265.18ω), signage (1,069,198.77ω), and building (1,064,385.91ω). In conclusion, the sky significantly attracts attention and stimulates emotions; the road improves navigation decision-making efficiency; buildings and other increases cognitive load; plants help alleviate stress; signage provides important information and directional guidance.

Analysis of the correlation between physical space and physiological characteristics. To explore the relationship between physical space quantification and physiological response in RDMB, this study conducted OLS regression analysis on the top 12 groups of SVIs with the highest click-through rates. The results show that the variance inflation factor (VIF) for the heritage environment indicators was less than 8, ruling out multicollinearity issues, indicating that the selection of indicators is reasonable (Table 3). The linear regression model analysis indicates that the model has a high explanatory power (R^2 > 0.5), especially for road and plant elements, where R^2 approaches 1, and the F-value is significant. Based on the street views of HTD, SVEs are categorized into immovable and movable elements.

The immovable elements include three categories: buildings, roads, and the sky. (1) The building element is negatively correlated with time to 1st view ($\beta = -0.17$, $P = 0.017$) and time viewed ($\beta = -7.585$, $P = 0.002$), but significantly positively correlated with fixations ($\beta = 2.114$, $P = 0.000$) and FPOGD ($\beta = 361.763$, $P = 0.003$). This suggests that buildings serve as

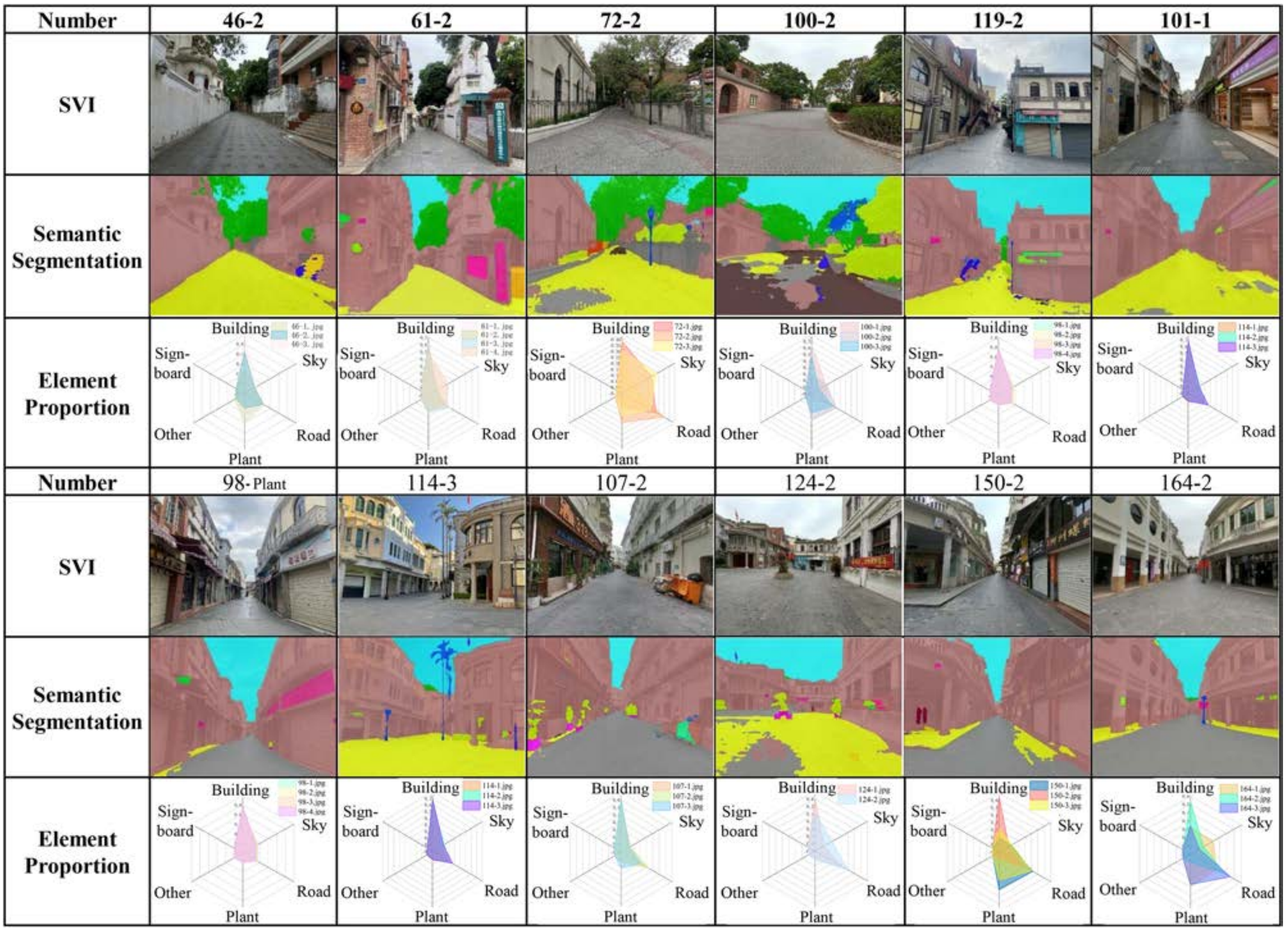


Fig. 10 Schematic of SVIs for 12 representative intersections and semantic segmentation metrics.

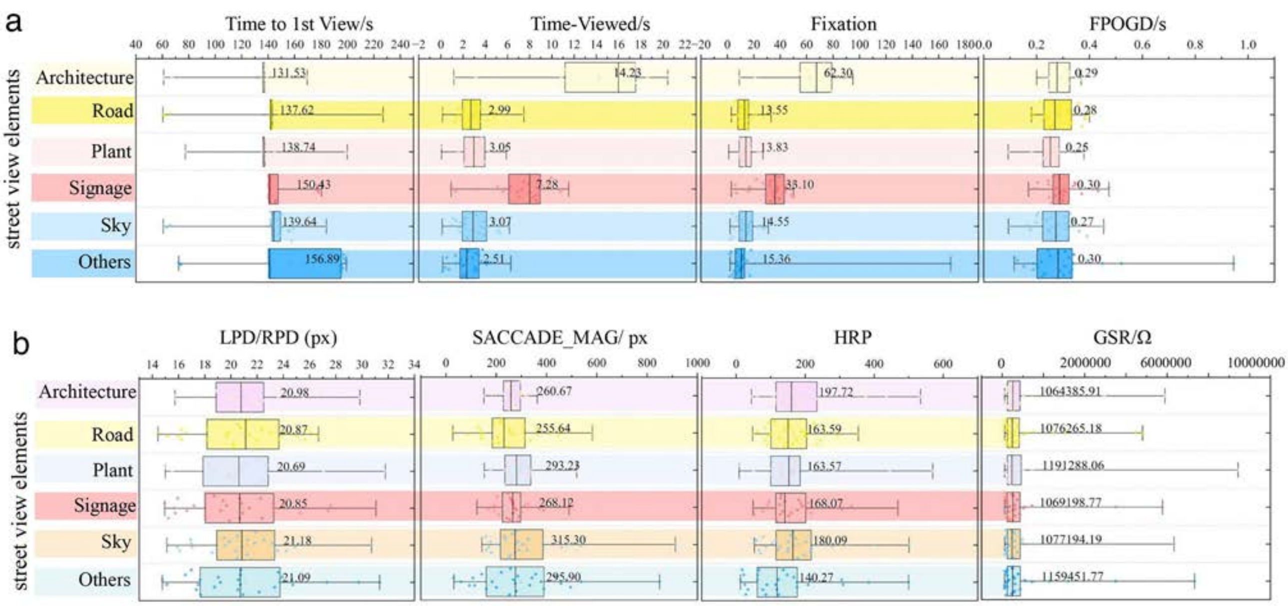


Fig. 11 Box plots of eye-tracking and physiological indices across different street view elements. a Eye-tracking indices. **b** Physiological indices.

visual focal points in RDMB, helping to quickly determine the route, but also increasing the cognitive load and the complexity of visual information processing. (2) The road element is positively correlated with time to 1st view ($\beta = 205.879$, $P = 0.013$) but negatively correlated with fixations ($\beta = -12.506$, $P = 0.006$), indicating that the visual appeal of roads is lower and requires more attention to form a memory. (3) The sky element is positively correlated with time viewed ($\beta = 2.411$, $P = 0.027$) and

Table 3 Linear regression model integrating eye-tracking and image segmentation data.

variable	building			road			Plant			signboard			sky			OSE		
	β	SE	p	β	SE	p	β	SE	p	β	SE	p	β	SE	p	β	SE	p
Time to 1st View	−0.17	0.066	0.017**	205.879	76.9	0.013**	−0.056	0.021	0.014**	−0.093	0.039	0.025**	−0.009	0.014	0.51	−0.007	0.008	0.381
Time Viewed	−7.585	2.195	0.002***	38.643	19.598	0.060*	2.138	2.176	0.335	−0.555	2.005	0.784	2.411	1.025	0.027**	0.004	0.001	0.008***
Fixations	2.114	0.467	0.000***	−12.506	4.181	0.006***	0.239	0.513	0.645	0.627	0.473	0.197	0.409	0.206	0.059*	0.545	0.291	0.073*
FPOGD	361.763	107.952	0.003***	−336.263	181.01	0.076*	−8.058	22.343	0.721	−2.246	41.766	0.958	−12.684	11.096	0.264	−8.076	3.638	0.036**
LPD	−1.28	1.444	0.384	3.36	2.57	0.203	0.541	0.548	0.333	−0.756	1.06	0.482	0.655	0.302	0.040**	0.06	0.23	0.797
RPD	1.863	1.117	0.108	1.987	3.864	0.612	−0.44	0.48	0.367	0.659	0.862	0.452	−0.262	0.301	0.393	−0.031	0.193	0.874
SACCADE	−0.05	0.048	0.301	−0.127	0.068	0.076*	0	0.011	0.977	0.016	0.027	0.558	−0.007	0.004	0.078*	−0.002	0.003	0.568
constant	−51.01	31.78	0.121	18.072	64.291	0.781	11.174	8.082	0.179	22.189	14.352	0.135	−2.726	4.274	0.529	2.877	2.442	0.25
R^2		0.702			0.684			0.562			0.563			0.901			0.572	
Adjusted R^2		0.607			0.591			0.421			0.491			0.869			0.411	
F	$F = 7.373$ $P = 0.000$***			$F = 2.506$ $P = 0.035$**			$F = 4.003$ $P = 0.004$***			$F = 2.691$ $P = 0.028$**			$F = 28.434$ $P = 0.000$***			$F = 3.563$ $P = 0.006$***		

LPD Left Pupil Diameter, *RPD* Right Pupil Diameter.
***, **, and * represent 0.01, 0.05, and 0.1 significance levels, respectively.

pupil diameter ($\beta = 0.655$, $P = 0.040$), indicating that the sky stimulates exploratory interest and emotional arousal, enhancing attention engagement.

The movable elements encompass vegetation, signage, and other SVEs. (1) Vegetation demonstrates a negative association with time to first view ($\beta = -0.056$, $P = 0.014$), reflecting reduced initial attentional capture by vegetative features. (2) Signage exhibits an inverse relationship with time to first view ($\beta = -0.093$, $P = 0.025$), implying diminished salience in primary decision-making phases and necessitating multiple fixations for informational verification. (3) Other street view components display a positive association with time viewed ($\beta = 0.0041$, $P = 0.008$) alongside a negative correlation with FPOGD ($\beta = -8.076$, $P = 0.036$), suggesting potential distraction effects and elevated cognitive load despite pronounced visual prominence.

Comprehensive analysis suggests that in optimizing immovable elements in HTD, building layouts should be simplified, and clear emergency signage should be installed to reduce cognitive load; road signage should be enhanced to improve visual appeal; and the emotional arousal effect of sky elements should be utilized to alleviate evacuation stress. Regarding movable elements, the positioning of plants and signage should be adjusted reasonably, and the placement of other facilities at intersections should be minimized to optimize sightlines and improve decision-making efficiency in emergencies.

Discussion

RDMB in HTD is critical to personal safety. Existing studies primarily examine RDMB in schools, underground spaces, and indoor environments. However, due to the long construction history and complex road networks of HTD, these environments may pose significant threats to personal safety during disasters and could lead to the destruction of heritage buildings, resulting in broader damage (Ferreira et al., 2016). This study, based on BDT and SOR theory, constructs an analytical pathway of P-P-P. Using SBSOD, scenario simulation, visual perception, and semantic segmentation technologies, SVEs are optimized based on human perception to guide evacuees' RDMB, thereby improving decision-making efficiency, as shown in Fig. 12.

Impact of psychological and cognitive stimuli on RDMB. By comparing planned evacuation routes with actual evacuation behaviors and incorporating the concept of bounded rationality from BDT, the study demonstrates that, in complex environments, decision-making is constrained by cognitive resources and emotional factors, which limit the ability to select the optimal path fully rationally. The study found that participants' familiarity with the location is positively correlated with the speed of finding emergency evacuation sites. This conclusion aligns with the research of Fang (Zhiming et al., 2020) and Fu (Fu et al., 2024), indicating that environmental familiarity simplifies the decision-making process and increases efficiency. Additionally, participants' planned evacuation routes were consistent with the shortest path, suggesting that when information is sufficient, individuals can effectively identify the optimal evacuation route. However, the complex terrain, unclear signage, and similar architectural styles in HTD significantly weaken the sense of direction, increasing decision complexity, and reflecting the disruptive effect of environmental factors on the decision-making process. Further analysis shows that participants with a stronger sense of direction exhibited less hesitation and lower heart rates (−0.988, -0.737) during decision-making, indicating that spatial orientation ability helps reduce cognitive load and physiological stress, thereby improving decision-making efficiency. The results

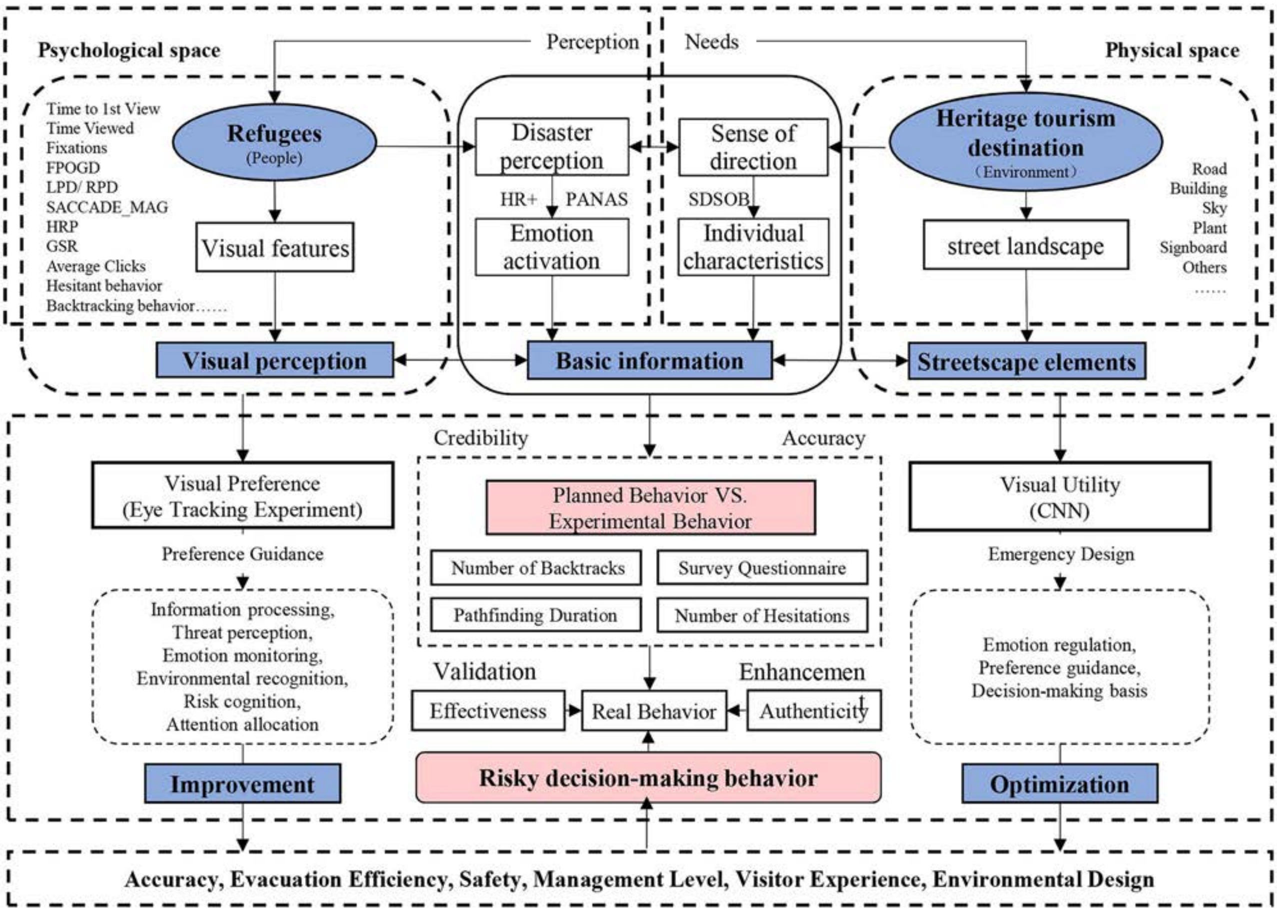


Fig. 12 The three dimensions of RDMB research.

suggest that individuals, when faced with complex environmental stimuli, rely on experience and cognitive abilities to simplify decision-making, operating within a state of bounded rationality. Based on this, emergency management in HTD should focus on enhancing residents' spatial orientation abilities, optimizing signage systems, and improving emergency response efficiency and safety through evacuation drills.

Impact of physical space quantification on RDMB. In risk decision-making research, the impact ranking of SVEs is as follows: building, road, sky, vegetation, others, and signage. Through click-through rate analysis, the ranking of elements is as follows: road, signage, building, sky, vegetation, and other elements, indicating that despite the low proportion of signage in street views, its higher click-through rate suggests that signage plays a key role in the decision-making process. SVI provides participants with intuitive visual cues. According to the heuristic decision-making model in BDT, individuals in complex environments often rely on intuition and experience for rapid decision-making. In this framework, signage, as a prominent visual stimulus, simplifies the decision-making process, especially in unfamiliar environments, where signage provides effective navigation cues. Based on the experimental results, it is recommended that an enhanced signage system be added at the 12 intersections prone to getting lost in Gulangyu's emergency evacuation system design to improve tourists' spatial orientation abilities, thereby enhancing emergency response efficiency and safety.

Impact of physiological responses on RDMB. Through eye-tracking experiments, this study explores the impact of environmental visual characteristics on spatial orientation decisions. Similar to the analysis of pedestrian trajectories and environmental factors using monitoring video data by Wei W et al. (Wei et al., 2022), this study further reveals that an open sky view can reduce psychological stress, supplementing the research by Wei Y et al. (Wei et al., 2023)on how enclosed spaces trigger anxiety responses. According to BDT, emotions and feelings play an important role in decision-making processes during emergencies, affecting decision efficiency and quality. Visual characteristics of the environment simplify decision-making through emotional regulation, reducing emotional burdens and enhancing spatial cognitive abilities. Particularly in emergency evacuations, clear visual cues can significantly improve decision-making efficiency. Based on this, it is recommended that heritage tourism destination designs ensure that similarly styled buildings are easy to identify to help tourists quickly locate their positions. Combined with bioelectrical indicators, the following optimization strategies are proposed: (1) In areas with high tourist traffic, shorten sunshades to open up sky views and reduce cognitive load; (2) Ensure that plants do not block signage; (3) Minimize the interference of other streetscape elements (OSE) (such as trash and commercial facilities) with decision-making, maintain a clean environment, and improve emergency response efficiency and decision quality.

Strategies and implications

Optimization strategies. Building on an analytical framework that integrates psychological and cognitive stimuli, assessment of the physical environment, and physiological responses, a two level optimization framework is formulated comprising a spatial

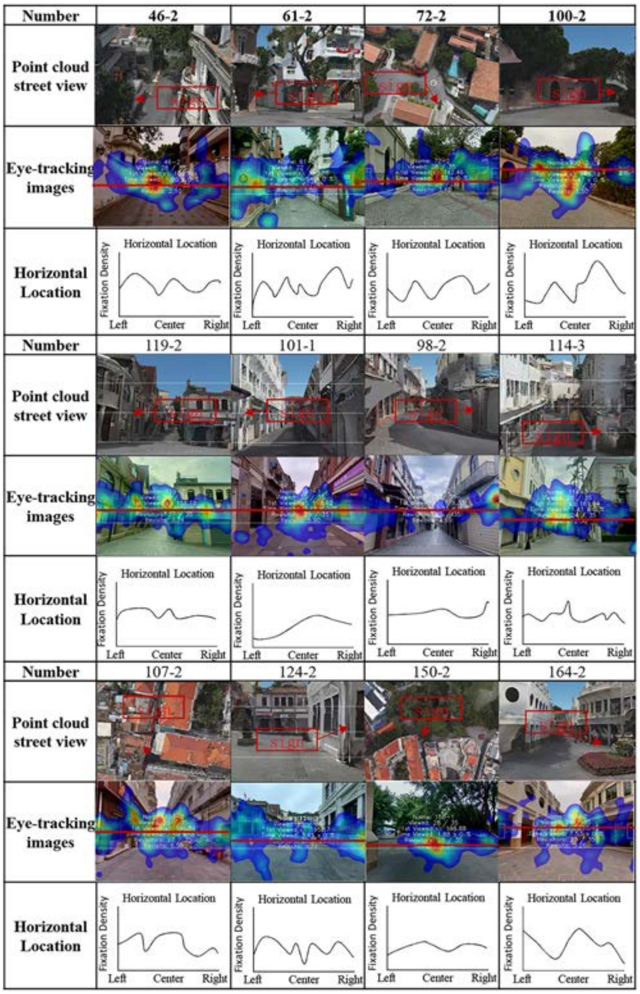


Fig. 13 Optimization of High-Risk Intersections Using 3D Models and Eye-Tracking.

environment layer and a stakeholder coordination layer. First, the spatial environment layer relies on a real scene 3D model combined with eye tracking heat maps and viewshed analysis to identify and optimize twelve junctions with a high risk of disorientation (Fig. 13). Second, the stakeholder coordination layer employs multistakeholder collaboration to extend site level measures to the area scale and to integrate them into routine governance processes (Fig. 14).

Spatial environment layer

Immovable Cultural Heritage: (1) The visual appeal and complexity of buildings increase the cognitive load of evacuees. For example, at intersections 114 and 101, similar architectural styles confuse the sense of direction. According to heuristic decision theory, individuals rely on prominent environmental cues to make decisions. It is recommended to install signage on key buildings to improve directional perception and enhance spatial orientation accuracy. (2) Road configuration plays a key role in decision-making, but in high-pressure environments, road concealment can hinder effective decisions. For instance, the wide intersection at 72 requires optimization of emergency signage placement to speed up response times. The narrowness of 107 Street limits sightlines, so it is recommended to place emergency signage on the walls of buildings in high pedestrian traffic. (3) Emotions significantly influence decision-making. Complex environments can induce anxiety and reduce decision-making efficiency. The sightline heatmap at intersection 114 shows that the enclosed spaces created by buildings restrict sky views, increasing emotional pressure. Therefore, it is suggested to reduce obstructions in this area to alleviate the psychological pressure caused by sightline closure.

Movable facilities: (1) The obstruction caused by dense vegetation affects sightlines, particularly at intersections 46, 100, and 150. It is recommended to adjust the distance between vegetation and signage to reduce interference. (2) In HTD, signage content should be clearer. It is suggested to use symbols and pictograms to enhance readability, and place signage in the order of buildings, roads, sky, plants, and other elements. (3) Other SVEs can distract attention and reduce decision-making efficiency. Considering that older residential areas often have randomly placed household items and commercial areas have sunshades that obstruct sightlines, it is recommended to reduce unnecessary infrastructure and maintain a clean environment to minimize visual interference.

Stakeholder coordination layer. (1) Residents: Research indicates a significant negative correlation (−0.562) between visit frequency and evacuation efficiency, suggesting that residents familiar with the environment are more likely to locate emergency shelters in times of crisis. Therefore, it is recommended to encourage residents to actively participate in regular emergency evacuation drills to enhance emergency response capabilities and take on the responsibility of guiding tourists during disasters. Additionally, disaster emergency knowledge should be disseminated through community activities and online platforms to improve residents' self-rescue, mutual aid, and cooperative rescue abilities, thereby enhancing evacuation efficiency. Furthermore, research shows that other SVEs ($\beta = 0.0041$, $P = 0.008$) are significantly positively correlated with Time Viewed, and significantly negatively correlated with the total distance of FPOGD ($\beta = -8.076$, $P = 0.036$), suggesting that these elements may divert attention and increase cognitive load. Therefore, it is recommended that residents reduce the placement of items on the streets and maintain a clean environment to reduce visual distractions.

(2) Tourists: Tourists can use applications or online platforms to view emergency shelters and evacuation routes, ensuring a transition from passive risk avoidance to active evacuation in emergency situations. Research indicates that 65% of participants exhibited a peak heart rate exceeding 100 BPM after watching the video. Based on this, it is recommended that tourists remain calm, follow guidance or signage, avoid overcrowding and confusion, and proceed to emergency shelters in a safe and orderly manner.

(3) Scenic area management: The Gulangyu Management Committee and urban planning managers should optimize the emergency signage system. Research indicates that, although the pixel proportion of emergency signage is relatively low, the click-through rate is high, and 79.41% of participants deviated from the expected evacuation path, making more than two detours, indicating the importance of emergency signage in evacuation decision-making. Therefore, it is recommended to install clear signage at key intersections and in areas prone to confusion. Eye-tracking data shows that tourists confirm orientation through buildings and signage and refer to elements such as plants, the sky, and roads. The study also found that the sky element is significantly positively correlated with time viewed ($\beta = 2.411$, $P = 0.027$) and pupil diameter ($\beta = 0.655$, $P = 0.040$), suggesting that open views help reduce cognitive load. Therefore, it is recommended to reduce obstructions from shading facilities to ensure unobstructed sightlines. Additionally, the plant element is negatively correlated with time to first view ($\beta = -0.056$, $P = 0.014$), indicating the need to trim plants to avoid blocking

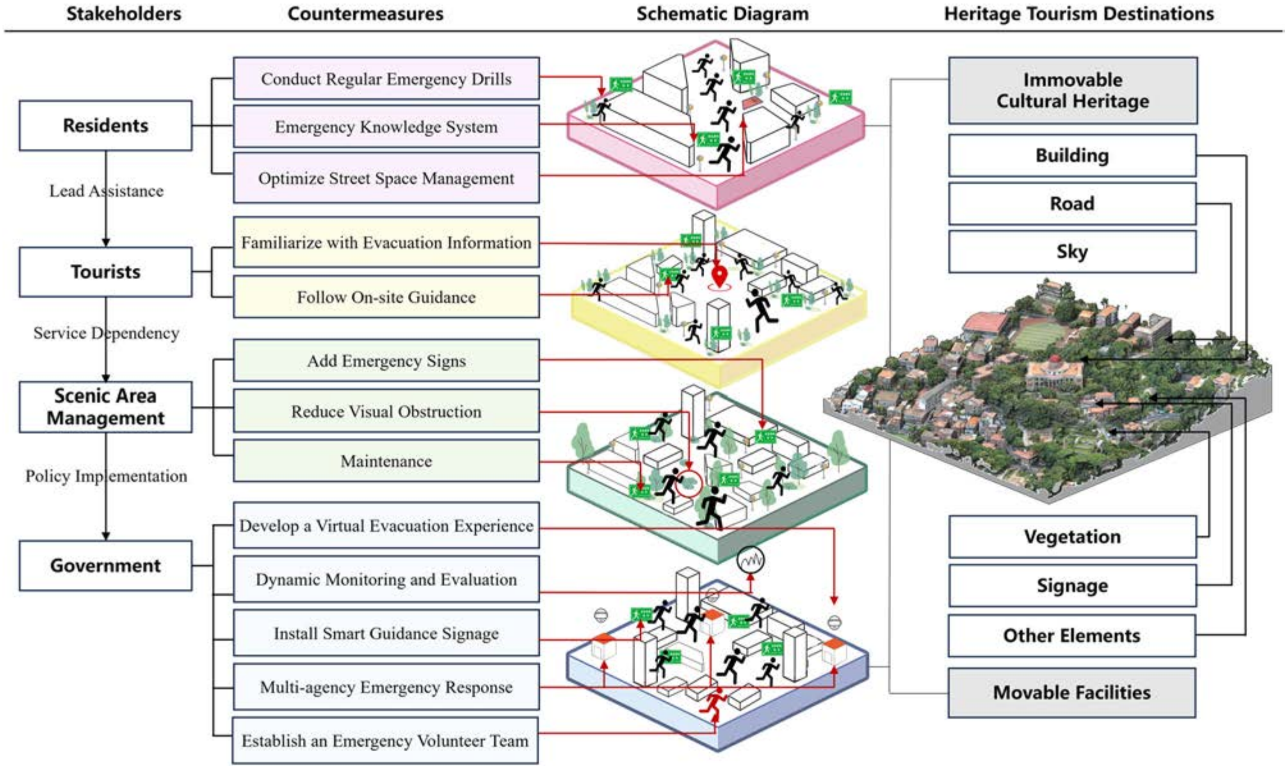


Fig. 14 Countermeasures and suggestions for stakeholders to enhance evacuation efficiency in HTD.

signage and improve visibility, thereby enhancing evacuation efficiency and reducing psychological burden.

(4) Government: The government should promote the use of SBSOD, scenario simulation, semantic segmentation, and eye-tracking technologies to develop VR/AR evacuation simulation experiences, enabling tourists to familiarize themselves with evacuation routes and shelter locations before arriving at the tourist destination, thereby enhancing emergency response capabilities. Additionally, the government should establish a dynamic monitoring mechanism to regularly assess the effectiveness of the signage system and optimize evacuation plans based on evaluation results. Furthermore, the government could install smart signage at key locations in the scenic area to enable real-time adjustments based on pedestrian flow and emergency needs, improving evacuation efficiency and enhancing tourists' sense of safety. To ensure efficient emergency response, the government should coordinate with scenic area management, medical, and firefighting departments to establish a collaborative mechanism to ensure coordination and efficiency in emergencies. Finally, the government should organize and train emergency volunteer teams to assist with evacuation and maintain order during peak periods.

Theoretical implications. At the theoretical level, first, the introduction of the SBSOD scale quantifies the impact of sense of direction on risk decision-making, expanding the application of BDT in individual differences and spatial perception. Second, by combining BDT with SOR theory, an integrated analytical framework of P-P-P is constructed, overcoming the limitations of traditional rational decision models and clarifying the impact of heritage tourism destination street environments on risk decision-making. Third, using semantic segmentation and eye-tracking techniques, the relationship between spatial perception and risk cognition is quantified, overcoming the limitations of traditional qualitative methods and offering new theoretical perspectives for behavioral science, environmental psychology, and disaster management. Finally, the mechanisms of the interaction between psychological cognition, physical space, and physiological features are clarified, enriching the theoretical framework of spatial perception and risk cognition and providing a theoretical foundation for further research.

Practical implications. At the practical level, based on the theoretical research findings, specific optimization strategies are proposed to address the emergency management needs in the complex environments of HTD, aiming to improve emergency response efficiency and enhance tourists' sense of safety. At the resident level, it is recommended to enhance self-rescue and cooperative rescue capabilities by regularly conducting evacuation drills and disseminating disaster emergency knowledge, thereby improving the overall emergency response capacity of the community. At the tourist level, it is suggested to optimize the signage system in the scenic area, particularly by adding clear and easily recognizable signage at key intersections and areas prone to confusion, to reduce cognitive load, improve navigation efficiency, and ensure effective evacuation during emergencies. At the scenic area management level, semantic segmentation and eye-tracking technologies are used to provide quantitative support for spatial planning and environmental design, optimizing tourists' spatial experience and strengthening cultural heritage protection. Finally, it is recommended that the government adopt advanced simulation technologies to help tourists familiarize themselves with emergency shelters and evacuation routes before arriving at the destination, promoting the shift from passive risk avoidance to active evacuation. Additionally, a dynamic monitoring mechanism should be established, coordinating with multiple departments, including scenic area management, medical, and firefighting services, to ensure multi-party collaboration, thereby improving emergency response efficiency and tourists' sense of safety.

Limitations and prospects

Limitations. This study has several limitations. First, the case context focused on built HTDs and did not include other destination types such as nature based tourism, leisure resort tourism, or ecotourism. The applicability of the findings to other destination settings therefore requires further examination. Second, the sample comprised mainly university students, with a relatively concentrated age structure and cultural background. The extent to which the results generalize to broader populations remains uncertain. Third, the experiment used a video based scenario to control variables and elicit responses, but this approach cannot fully capture dynamic disturbances and multisensory stimuli in real disaster environments. Fourth, the study relied primarily on visual information and used eye tracking metrics to describe gaze distribution and information search during the task. These metrics characterize attention allocation and should not be treated as direct measures of emotional intensity or decision motivation. Because auditory and tactile information were not included, and social interaction and cooperation were limited under laboratory conditions, group interaction factors were not fully represented. Fifth, at the technical level, DeepLabv3+ was used to extract visible streetscape elements, but performance may be affected by image quality, occlusion, and model generalizability. In addition, recognition of heritage building attributes such as age, category, and fine morphological details remained limited, and the approach may require substantial computational resources.

Prospects. To address the above limitations, future research can be improved in the research object, experimental sample, design, methodologically and technical methods. First, with respect to the research object, expand the empirical scope beyond architectural HTDs to include nature tourism, leisure resorts, and ecotourism in order to improve contextual generalizability (Maria et al., 2016). Second, regarding the experimental sample, diversify participant characteristics across age, cultural background, and occupation to strengthen validity. Third, in terms of design, complement video based laboratory protocols with in situ or simulated settings that incorporate social interaction and group collaboration; integrate augmented reality and metaverse platforms to approximate the complexity of disaster scenes (Gu et al., 2023; He et al., 2025). Fourth, methodologically, the experimental design should incorporate additional biological signals, such as electroencephalography (EEG) (Cruz-Garza et al., 2022; Kalantari et al., 2022), electromyography (EMG) (Alibhai et al., 2020), and acoustic or tactile feedback (Chelladurai et al., 2024), to increase the sense of immersion and realism in disaster scenarios. Fifth, from a technical perspective, future research should optimize existing algorithms to reduce computational resource requirements and combine other DL models to improve the accuracy of recognizing fine-grained features of heritage buildings (e.g., age, style, material) (Abusaleh, 2024; Tan et al., 2024), thereby providing more precise support for RDMB in architectural HTD.

Conclusion

This study combines SBSOD, scenario simulation, semantic segmentation, and eye-tracking experimental techniques to explore the optimization pathway of RDMB in HTD. The analysis is conducted from three aspects:

(1) Psychological cognitive stimulation: The unique planning mechanisms of HTD may lead evacuees to experience disorientation. Participants with stronger sense of direction exhibited fewer hesitation behaviors and lower heart rates (-0.988, -0.737), and males generally had a better sense of direction than females ($P = 0.439$). The higher the frequency of visits to Gulangyu prior to the experiment, the faster the participants were at finding emergency shelters (-0.562). The experiment duration was positively correlated with the number of detours (0.845) and negatively correlated with visit frequency (-0.571). The number of hesitation behaviors was positively correlated with heart rate (0.698), indicating that more hesitation resulted in higher heart rates, reflecting psychological stress in the risk decision-making process.

(2) Physical space quantification: The ranking of SVIs affecting RDMB is as follows: architecture (54.19%), roads (25.49%), sky (9.97%), greenery (9.62%), OSE (0.43%), and signage (0.29%). Notably, although participants initially showed limited attention to emergency signage, focus on these signs increased as the frequency of BTB grew.

(3) Physiological characteristic response: In RDMB at HTD, participants initially use architectures and signage to determine their location, then observe the environment using other elements such as vegetation and the sky, and finally enhance their navigation efficiency through other facilities and road elements.

(4) Correlation analysis of physical space and physiological indicators: Immovable cultural heritage features, such as complex building layouts and road configurations, increase cognitive load, while open skies help alleviate the psychological burden of wayfinding and improve adaptability. Adjusting the location and number of movable facilities, such as plants, signage, and other SVEs, can effectively guide RDMB and enhance wayfinding efficiency. Specifically, reducing vegetation coverage at intersections and adding directional signs at complex junctions can help improve RDMB and enhance the clarity of visual guidance. Additionally, reducing the placement of OSE at intersections and maintaining a clean and orderly street environment can help shorten wayfinding time.

In summary, this study adopts a human-centered approach, integrating BDT and SOR theory to construct an analytical framework of P-P-P. By comparing the differences between planned and actual behavior paths, and utilizing eye-tracking experiments and semantic segmentation techniques, the study explores the impact of street view intersection features on BTB and disorientation tendencies. This research provides a theoretical basis for optimizing evacuation guidance systems in HTD, enhancing tourists' sense of safety, and improving disaster response efficiency. It also offers practical optimization suggestions for the planning and management of HTD, facilitating the effective translation of theoretical research into practical application.

Data availability

De-identified datasets and supporting documentation are available through a private Figshare repository: https://figshare.com/s/724376245a7a3b8fcc4b. Public release is restricted due to ethical and privacy considerations. De-identified materials may be made available upon reasonable request to the corresponding author, subject to appropriate safeguards.

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Author contributions

YD conceptualized the research, designed the methodology, and wrote the original draft. YL supervised the research and acquired funding. MY conducted the investigation, collected data, visualized and validated results, and reviewed and edited the manuscript. YW collected data. HB contributed to the investigation. JH contributed to the investigation. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Ethical approval

This study involved human participants and their data. All research procedures were conducted in strict compliance with the ethical standards established by Chinese institutional and national research ethics committees, as well as the principles outlined in the Declaration of Helsinki and its subsequent revisions or equivalent ethical guidelines. Ethical approval for this research was granted by the Ethics Committee of the School of Architecture and Civil Engineering at Xiamen University (Approval No. XMU-IRB-2023-1101-016), with the approval officially issued on November 1, 2023. The approval covers all aspects of the study, including participant recruitment, data collection, and data analysis. The study was officially launched after obtaining ethical approval, and no data collection was conducted prior to approval. Throughout the research process, the rights, safety, privacy, and well-being of participants were rigorously safeguarded in accordance with the approved protocols and relevant Chinese regulations.

Informed consent

Informed consent was obtained from all participants involved in this study. Participants were adults aged 18 years or older, with full legal capacity, and no vulnerable groups, such as minors or patients, were involved. Participants were informed that their participation was voluntary and that they had the right to withdraw at any time without penalty, after being provided with detailed information regarding the study's objectives, procedures, data usage, confidentiality measures, potential risks, and their right to withdraw without consequence. The informed consent form was presented on the first page of the questionnaire, and participants could proceed to the main survey only after reviewing the information and explicitly confirming their consent. Data collection occurred between December 1, 2023, and December 31, 2023, and all responses were collected anonymously, with no personally identifiable information gathered. The data collected will be used solely for academic research and published in anonymized form, ensuring full protection of participants' privacy and data security.

Additional information

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