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A quantitative evaluation method for ritual design expression in case studies of traditional Chinese architecture

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Ritual constitutes a bidirectional interaction between humans and environments, necessitating quantitative evaluation methods for ritual design expression. Traditional evaluation methods primarily rely on qualitative judgments, lacking quantitative processes. This study proposes a novel quantitative framework integrating environmental simulation and agent-based modeling to assess ritual design expression in architecture. Four traditional ritual buildings (faith-based, ceremonial, political, secular) and two non-ritual spaces were analyzed. Key steps included: (1) digital modeling of ritual procedures and spatial parameters; (2) agent-based simulation (Anylogic platform) tracking compliance with ritual paths; (3) development of evaluation criteria grounded in existing theories and scientific hypotheses; (4) quantification via metrics like path alignment and behavioral consistency. The validation results demonstrate the effectiveness of this quantitative evaluation approach. This study also discusses the practical value of the evaluation tool and future research directions, informing the preservation of traditional ritual architecture and the innovation of modern ritualistic spatial design.

Human senses (e.g., heat, cold, pain, orientation) and cognition (e.g., memory, knowledge, imagination) in physical space collectively shape an individual's perception of their current environment[1]. This perception is reflected in many aspects, including behavioral guidance, cognitive processes, social interactions, and mental health. Generally, the extent to which individuals engage with their environment is contingent upon their level of satisfaction with it. Consequently, architectural space can intentionally shape the environment to fulfill the functional needs of users, thereby enhancing user satisfaction and improving the interaction between individuals and their built surroundings. Individuals' perceptions of the environment and their behavioral experiences in buildings are crucial for effective building design and post-occupancy evaluation. This study is the first to introduce the social force model and agent-based simulation technology into the evaluation of ritual architecture, aiming to propose a set of evaluation tools for ritual environment design through quantitative analysis of individual behavioral dynamics in ritual spaces.

Existing research generally focuses on the impact of architectural physical environmental parameters (such as thermal, light, and sound) on human physiological and psychological perception. Du et al.[2] examined indoor environmental perception through questionnaires, physiological monitoring, and facial expression recognition. Wu et al.[3] investigated how various indoor environmental quality factors influence patients' perceptions in hospitals. Yang et al.[4] analyzed the effects of classroom lighting and sound

factors on the cognitive performance of students attending classes. Choudhary et al.[5] simulated human physiological behaviors in warm and hot environments through a modified human thermoregulation model. However, fewer studies have explored the impact of building environment design on individuals' perceived behaviors. Zhang et al.[6] investigated the relationship between restorative office space design and employees' stressors, environmental satisfaction, and well-being through interviews and a literature review. Qiao et al.[7] examined the influence of environmental perception on walking behavior, developed a conceptual model, and collected big data using a real city as a case study. The article suggests that individuals' walking behavior is significantly influenced by their personal perceptions of the surrounding environment. While Qiao et al. focus on the empirical investigation of the role of individual behavior in relation to environmental perception, their study lacks simulation and predictive analyses. This study aims to quantitatively investigate the behavior and perceptions of individuals in various spatial environments with different design expressions through the method of environment-human behavior simulation, and to develop an evaluation tool for environmental design.

Ritual architecture refers to buildings or groups of buildings that are designed and constructed to support and promote the performance of particular rituals or ceremonies. These spatial environments are typically closely associated with religion, culture, and social practices. They serve not only as physical spaces that carry ceremonial behaviors, but also as vessels

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for conveying cultural meanings and fulfilling social functions. Current research on ritual architecture is dominated by two mainstream paradigms: "spatial archeology" and "symbolic hermeneutics." The former focuses on the historical evolution of ritual space forms[8–10], while the latter emphasizes the interpretation of symbolic elements in ritual culture[11–14]. However, both paradigms overlook the essential function of ritual architecture—regulating user behavior patterns and collective psychological states through spatial environment design, thereby facilitating the occurrence and progression of ritual activities. Therefore, this study selects the evaluation of ritual architectural environment design as its research objective and employs quantitative tools to validate the "environment-behavior-meaning" transmission mechanism in ritual spaces.

Agent-based simulation is an individual-based modeling approach used to simulate the dynamic behavior of complex systems. The attributes of agents include autonomy and interactivity; by simulating individual behaviors, macroscopic phenomena at the group level can be observed[15]. Pedestrian simulation is a specific application of agent-based simulation, which establishes a pedestrian motion model based on the collection of people's behavioral data. This approach intuitively portrays pedestrian behavior through either discrete event or continuous event simulation[16]. Pedestrian simulation based on social force model is widely utilized in architectural planning to study traffic organization, pedestrian evacuation, and spatial layout optimization, among other applications. Cheng et al.[17] simulated the avoiding behavior mechanism of individual pedestrian by introducing inertia coefficients. Kaziyeva et al.[18] developed a large-scale agent-based simulation model of pedestrian traffic to analyze pedestrian traffic flow in urban areas. Filomena et al.[19] proposed an empirical agent-based model to simulate pedestrian movement in cities, taking into account behavioral heterogeneity in pedestrian route choice strategies.

Based on established research, this study develops a simulation experiment process as an evaluation tool and formulates judging criteria. In the Results section, traditional Chinese buildings are selected as experimental subjects to validate the evaluation tool. To enhance the accuracy and credibility of the validation conclusions, both positive and negative cases are chosen for comparative validation. The Discussion section summarizes the characteristics and design influences of the ritual environment, revealing the design principles underlying the ritual expression of traditional Chinese architecture. Additionally, it explores the application scenarios of the design tool and analyzes the limitations of the current research methodology, as well as the potential for future development.

Methods
Research objects
Traditional Chinese architecture is the most explicit carrier of rituals, and the study selects typical traditional ritualistic architecture as positive cases for instrumental validation. According to different social and cultural attributes, traditional ceremonial architectural spaces can be categorized as faith spaces, ritual spaces, political spaces and secular spaces[20].

The cases selected in this paper are all representative, their spatial environment ritual design expression is widely recognized, and the environmental status quo is complete and easy to research. Considering the objective conditions of satisfying the investigation on ritual contents and facilitating modeling, the following four representative samples of different ritual space types were selected as research objects in this paper: Meidaizhao Mahavira Hall, Temple of Heaven Huanqiu Altar Complex, Neixiang County Yamen and Liping Tang'an Dong Village (Fig. 1, Table 1).

In order to enhance the credibility and persuasiveness of the case simulation results and make the tool validation conclusions more accurate and reliable, two typical samples of non-ritualized spaces are selected for comparative study in this paper. For example, in a traditional craft production workshop, professionals under the guidance of a certain process will carry out production activities in accordance with the prescribed order in the spatial environment; while the spatial behaviors of non-professionals may be random and disorderly when they occur.

pottery workshop: The spatial environment of traditional pottery making is closely linked to the pottery making process, including not only the physical space required for pottery making, but also the cultural and social contexts that are compatible with it[21].

Medium-sized lecture hall: A contemporary secular space that provides the physical environment required for activities such as academic lectures and conference presentations, creating an atmosphere conducive to interactive communication and collective learning.

Software Selection
The objective of this research paper is to design a tool for the environmental ritual evaluation of buildings of ceremonial nature. To achieve the

Fig. 1 | Photographs of cases. a Meidaizhao Mahavira Hall. **b** Temple of Heaven Huanqiu Altar. **c** Neixiang County Yamen. **d** Tang'an Dong Village. **a–d** show field photographs of four selected traditional Chinese ritual architecture case studies.

a. Meidaizhao Mahavira Hall

b. Temple of Heaven Huanqiu Altar

c. Neixiang County Yamen

d. Tang'an Dong Village

Table 1 | Case Studies Information

Architecture names	Meidaizhao Mahavira Hall	Temple of Heaven Huanqiu Altar Complex	Neixiang County Yamen	Liping Tang'an Dong Village
Architecture type	Religious architecture	Ritualistic architecture	Official architecture	village architecture
Space type	faith space	ceremonial space	political space	secular space
Space type connotations	Spaces for individual or collective faith activities, mostly churches and temples for witchcraft activities or worship activities, such as Meidaizhao, Foguang Temple	Spaces dedicated to or used as the main function of liturgical activities, mostly for the ancient Chinese halls, palaces, etc., such as the Temple of Heaven in Beijing, the Altar of Land and Grain	Spaces associated with state power and where political ceremonial activities take place, such as the Neixiang County Yamen, the Forbidden City Taihe Gate	Spaces serving daily production and living, including homes, villages, etc., such as Tang'an Dong Village, Yurt
Site context	The only existing Tibetan Buddhist temple in China where 'people and gods live together and the city and temple are combined'[41]	The world's largest existing complex of buildings to worship the heaven; the place where emperors of the Ming and Qing dynasties made heavenly sacrifices[42]	Feudal times, county-level government offices, known as the 'world's first Yamen'[43]	Located in the Dong ethnic area of Guizhou Province, it is a typical representative of Dong villages in Southwest China[44]
Ritual purpose	Buddha Worship, Prayer for Blessings	Auspicious Rites, Great Sacrifices, Heaven worship	Defend the political regime	Daily routine
Ritual behavior	Devotees participate in the blessing ceremony	The Emperor and his ministers made heavenly worship on the Winter Solstice	Inauguration of local officials	Daily Life Rituals of the Dong People

quantitative evaluation, AnyLogic has been selected as the primary software platform for the tool's design.

Social Force Model (SFM) is a model used to simulate pedestrian flow and crowd evacuation behavior. It is characterized by its capacity to describe pedestrian behavior both efficiently and accurately. The fundamental principles of the model include goal-driven, repulsive, and attractive forces[22]. One of the key advantages of such models is their ability to quantify the environmental goals and behavioral preferences of individuals. In Anylogic, the Pedestrian Library utilizes a social force modeling algorithm to simulate how pedestrians respond to their surroundings, where pedestrians follow the shortest path principle of walking while taking into account interactions with others or obstacles in the environment[23]. In the fixed-place model, the complex movement behaviors of individuals are categorized into turning, overtaking, converging, and diverging, based on pedestrian movement tendencies. Additionally, the behavioral decisions of individuals influence the movement tendencies of the group. For these reasons, this study selects the SFM as an experimental design tool to simulate the ritual activities of pedestrians in a ritual scenario and to examine the behavioral characteristics of individuals within the simulated environment.

To verify the effectiveness of the social force model simulation software in simulating and predicting pedestrian behaviors in ritual environments, this study employed a questionnaire-based survey to collect and analyze real-world pedestrian behavior pattern data from Case 1: Maidai Zhao Mahavira Hall. Statistical results demonstrate that agent-based simulation technology can effectively capture and simulate pedestrian behaviors (e.g., staying, turning, detouring) within architectural environments to a significant extent.

AnyLogic is a software platform designed for modeling and simulating discrete events, system dynamics, multi-agent systems, and hybrid systems[24]. Its application areas encompass the logistics industry, pedestrian transportation, service systems, ports and airports, and the spread of diseases[25–27]. Currently, there are relatively few studies that utilize AnyLogic for analyzing the correlation between spatial environment and human behavior. Chen Yue et al.[28] employed AnyLogic to simulate visitor behavior in historical districts and optimize their design. Wu Yan et al.[29] investigated the configuration of spatial elements in community parks based on the activity patterns of the elderly. Ling Wei et al.[30] simulated the movement trajectories of individuals, examined the impact of spatial flow patterns on human behavior, and proposed optimization strategies for flows in college libraries.

Based on Anylogic platform, model construction is mainly a process of plan construction and parameter configuration. Plan construction includes functional division, attraction point setting, and agent-based point arrangement. Parameter settings include the fundamental agent-based behavioral parameters, simulation running time, and route selection probability settings. This experiment mainly applies the pedestrian library panel of Anylogic software, which is divided into two areas: space markers, modules. The spatial markup tool is employed for modeling the built environment; the modular tool is used for writing the logic flow of pedestrian behaviors. Simulate pedestrian ritual behavior in a ritual space by adding environmental elements such as walls, services, and attractors (Table 2).

Evaluation methodology

The research route of this paper is divided into three steps (Fig. 2):

- Using simulation software, designing environment-human behavior simulation experimental process as an evaluation tool, the experimental content is scenario analysis and agent ritual behavior prediction of the evaluated object's architectural environment.
- Establishing criteria for judging architectural ceremonial design expressions based on established research theories and pre-critical analyses of model data.
- Defining the validation criteria for tool effectiveness, and selecting both positive and negative case samples to verify the validity of the tool.

Table 2 | Pedestrian Library tool—Ritual simulation instruction comparison table

Module name	Instruction Description	Ritual simulation instructions
Ped Source	agent-based generation points	Ritual process starting point
Ped Sink	agent-based vanishing point	Ritual process end location
Ped Go To	agent-based destination	Ritual participants walking behavior, such as monks circling to pray for blessings
Ped Wait	agent-based waiting behavior	Ritual stay behavior, such as kneeling to the buddha
Ped Select Output	Set up conditional statements to control process branches	Choice settings for different ritual paths for ritual participants
Target Line	Set the target line	Define the location of space entrances and exits
Polygonal Node	Draw polygonal areas	Irregular activity areas, such as temple of Heaven Huanqiu Altar Complex
Rectangular Node	Draw rectangular areas	Rectangular areas for ritual activities, such as the Buddha Hall area
Pathway	Draw the defined path	Set up fixed ritual routes
Attractor	Place the attractor	Control the attraction of ritual activity areas to pedestrians
Density Map	Density map	Visualization of pedestrian flow density

Step 1: Construct an evaluation tool.

1. Conduct field research, data collection and image acquisition for selected architectural cases. Analyze the ritual procedures and environmental information of each case, abstractly extract, and draw diagrams of ritual nodes (Diagram n-S).
2. Import the floor plan of the case into Anylogic software, model the physical environment of the site, the behavior of the people and improve the basic parameter settings. Taking whether pedestrians follow the ritual process in this architectural space as a variable, two sets of behavioral logic flows are written, namely, aimless walking logic flow (Logic n-A) and ritual route logic flow (Logic n-B). In different case studies, by independently programming Logic n-A and Logic n-B, a clear mechanism is established to distinguish between pedestrians' spontaneous movements and behaviors following ritual procedures.

    Logic n-A: The entrance and exit spaces of the case study site are set as the starting positions for agent pedestrians; large-area environments are designated as reachable and habitable regions for agents, ensuring coverage of the ritual space; all possible paths are programmed, and the path selection probability for agents is randomized through custom Java code, thereby simulating the spontaneous behavior of pedestrians.
    Logic n-B: This is specifically programmed according to the ritual procedures of each case study; precise ritual routes and prescribed ritual behaviors are defined; as shown in Table 2, agent actions are programmed with specific instructions to ensure that their behaviors adhere to fixed ritual procedures.
3. Incorporate a crowd density heatmap tool during the simulation process for each case to visualize the simulated data. Different logic flows generate corresponding heatmap results: Heatmap n-A (HM n-A) and Heatmap n-B (HM n-B).
   • HM n-A displays agent spatial density distribution based on Logic n-A (spontaneous behavior logic), reflecting fundamental spatial attraction characteristics of the built environment.
   • HM n-B presents agent spatial density distribution based on Logic n-B (ritual behavior logic), demonstrating how spatial environments guide specific ritual behaviors.
4. Simulation result analysis method: at least four spatial nodes with clear ritual behaviors occurring are selected for the evaluation case, and their differences and similar features in each information image (Diagram n-S, HM n-A, HM n-B) are compared and qualitatively described based on visual cognitive judgment.

Step 2: Establish evaluation criteria.

1. The establishment of evaluation criteria is based, on one hand, on the design experience of ritual spaces, and on the other hand, on scientific hypotheses derived from the simulation results of case samples. Existing research on ritual spaces has summarized the fundamental logic of ritual architectural environment design, which is that the design of a defined space should meet the specific functional and spiritual needs of its users in the context of rituals. The perspectives proposed by various scholars on the expression of ritual in architectural design have laid the theoretical foundation for the evaluation criteria of this study (Table 3).
2. Based on the systematic review of the above literature, this study defines "effective ritual space design" as a spatial environment with the ability to guide ritual behavior, symbolize ritual culture and immerse in ritual perception. Grounded in this theoretical framework, four evaluation criteria are established through integrated visual image analysis and experimental data comparison, using path compatibility, behavioral consistency, and space utilization as key metrics. The preset criteria are as follows:
    i. Whether there is an opportunity for ritual occurrences embedded in the built space;
    ii. Whether the built spatial environment aligns with the corresponding ritual behavior;
    iii. Whether the built environment exerts a disciplinary effect on the spatial subject, and analyze the mechanisms underlying this effect;
    iv. Whether this disciplinary effect effectively promotes the occurrence of ritual behaviors in the built environment.
3. During the simulation process of different logic flows (Logic n-A, Logic n-B), if the dynamic simulation conditions of the agents show greater convergence with actual sample survey records or historical research data, it can be determined that the built environment possesses ritual occurrence potential, meaning the case sample meets criterion i.
4. Conduct comparative analysis between HM n-A and HM n-B by observing the similarity of heatmap distribution patterns in ritual node areas. If over half of the selected spatial node images demonstrate significant similarity, it indicates that the built environment of the sample case exhibits relatively strong compatibility with ritual behaviors, thus meeting criterion ii. The degree of compatibility between the spatial nodes and the ritual behaviors can be categorized as high, average, and low.
5. Observe the visual performance of HM n-A under different simulation durations. If agent pedestrians exhibit distinct and stable behavioral states in the simulated environment, it will be considered to meet criterion iii. Additionally, analyze the mechanism of environmental influence on pedestrians in this case by referencing Diagram n-S comparison, clarifying the correspondence between spatial design elements and behavioral constraints.
6. Finally, based on the judgment conclusion of criterion iii combined with on-site case photographs or historical scene images, if the behavioral trends and path selections of pedestrians during the simulation process demonstrate substantial consistency with the actual
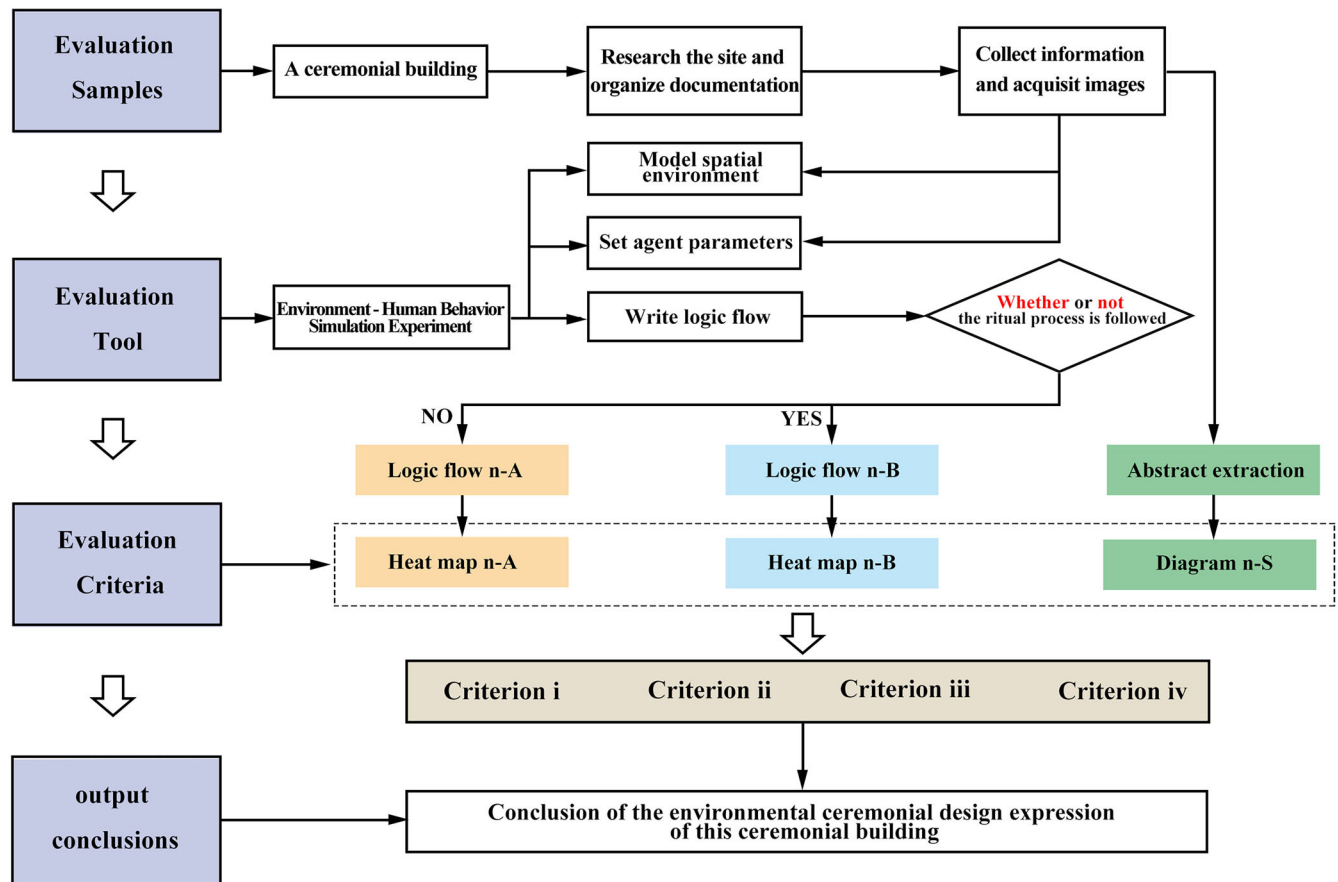
Fig. 2 | Evaluation flowchart. Flowchart of the building case evaluation process.

Table 3 | Content of Existing Research Literature

Researcher	Literature	Content
Norberg-Schulz	*Genius Loci: Towards a Phenomenology of Architecture*	Focuses on the dominant role of place environment on human behavior, emphasizing that architectural design should reflect and preserve users' sensory experiences in specific contexts[45].
Pier Vittorio Aureli	*Rituals and Walls: The Architecture of Sacred Space*	Explores the definition and characteristics of sacred space; analyzes how sacred spaces use architectural forms to create a distinct experience separated from secular spaces[46].
Xujia Chen	*Creating a Sense of Ritual in Landscape Design*	Provides a detailed analysis of ritual atmosphere cultivation in landscape design, proposing methods such as visual focus, behavioral constraints, and psychological pressure to enhance ritualistic experiences[47].
Baojun Miao	*Research on the Design of Ritualistic Architectural Spaces*	Argues that modern ritualistic architectural spaces should satisfy emotional richness, preserve collective memory, and offer spiritual faith and psychological comfort to users[48].
Zhiqiang Zou, Weifeng Xu	*Analysis of Ritualistic Shaping in Architectural Spaces*	Elaborates on the influencing factors and design strategies for cultivating a sense of ritual in architectural spaces[49].
Spiro Kostof	*A History of Architecture: Settings and Rituals*	Through a comprehensive review of architectural history, examines the profound relationships between architecture and environment, society, culture, religion, and rituals[50].

ritual occurrence state depicted in the scenes, the case is determined to comply with criterion iv.

Step 3: Validation of the tool.

1. The evaluation tool designed in this study needs to meet the following validity conditions:

Spatial differentiation capability. The experimental simulation results should exhibit significant spatial typological differentiation, clearly demonstrating through visualization data the distinct pedestrian behavior patterns between ritual and non-ritual spaces. In ritual environments, agents display orderly aggregation such as axial directional movement, whereas in non-ritual environments they exhibit aimless wandering with random spatial distribution. The spatial typological differences demonstrated by the tool are principally manifested in three key aspects: crowd aggregation patterns, consistency of movement direction, and organization of flow trends.

Historical corroboration capacity. Evaluation conclusions derived from the tool must show substantial alignment with qualitative findings from traditional architectural historiography. Specifically, simulation outcomes need to conform to documented ritual functions of the spatial environment as evidenced in historical literature or empirical research - for instance, the simulated agents' worship procession paths should match ritual procedures recorded in archival documents.

Mechanistic interpretability. The behavioral metrics of agent populations in simulations (e.g., path compliance rate, behavioral synchronization rate) must demonstrably reflect and explain how spatial environmental parameters (including path width, courtyard layout, and visual corridors) exert behavioral guidance and disciplinary effects on users, along with their underlying physical mechanisms.

2. This study establishes both positive and negative control groups through case selection. The positive cases comprise four representative traditional Chinese ritual buildings (one each for faith, ceremonial, political, and secular spaces), ensuring coverage of major ritual architectural typologies; the negative controls include one non-ritual traditional architectural space and one contemporary secular space, serving to verify the tool's discriminative capacity.

3. Validity confirmation requires: all positive cases yield positive environmental evaluation results while all negative controls produce negative evaluations; and key metrics in the positive case group—including path compliance (spatial overlap rate between HM n-A and HM n-B) and behavioral synchronization rate (matching degree between agent action sequences in HM n-A and ritual procedures in Diagram n-S)—demonstrate statistically significant superiority over those in negative cases.

Results

Meidaizhao Mahavira Hall

The Mahavira Hall is the largest hall in both area and volume within the Meidaizhao Monastery. It is located in the first node of the architectural axis. As the most theocratic characteristics in the Meidaizhao architectural complex, it is composed of a porch, a scripture hall, and a Buddhist hall. It follows the typical layout of "scripture hall in the front, Buddha hall in the back." And it serves as a space for monks to conduct daily chanting rituals, perform sacrificial ceremonies, and where believers worship the Buddha[31].

The New Year Prayer Dharma Assembly held annually in the lunar January is the most important ritual event at Meidaizhao Monastery, and the Mahavira Hall is the main venue for this prayer ritual. In the first route, participants enter the scripture hall and then turn right to proceed in the prayer wheel direction to enter the outer corridor of the rear hall (chanting passage). After that, they circle around the rear hall while praying, and walk out the hall along the prayer wheel path. In the second route, participants enter the prostration area in the rear hall in a clockwise direction. They may either perform prostrations in front of the Buddha statue or circumambulate the statue as an act of devotion. Finally, after all the ritual events, they exit the hall by following the direction of the prayer wheel path.

Spatial nodes of ritual occurrence. prayer wheel path, rear hall prostration area, circumambulation path of the rear hall, rear hall outer corridor.

Actual Pedestrian Behavior Data. A survey questionnaire was distributed to visitors of MeidaiZhao, with 22 valid samples collected (Table 4). The data revealed that visitors paused at all four major ritual nodes within Meidaizhao Mahavira Hall, accompanied by simple ritual behaviors (Appendix 1 Survey Questionnaire on Pedestrian Behavior in Ritual Spaces).

1. At the prayer wheel path: 90% of visitors entered the scripture hall clockwise and touched the prayer wheels as part of their ritual experience.

2. In the rear hall prostration area (in front of the Buddha statue): 27.2% of visitors stayed for extended periods to perform prostration rituals and blessings, while 72.7% paused briefly to observe.

3. Along the circumambulation path of the rear hall: 27.2% of visitors performed clockwise circumambulation around the statue.

4. In the rear hall outer corridor: 54.5% of visitors engaged in clockwise circumambulation while chanting sutras.

Visitors' behaviors within the spatial environment were influenced by multiple factors: architectural layout and path organization (63.6%), religious symbols and environmental design (54.5%), and the tendency to follow

Table 4 | Questionnaire Results Statistics

Variables	*n* (%)
1. Are you familiar with the religious cultural background or related ritual activities of Meidai Zhao Temple?	
a. Very familiar	2 (9.09%)
b. Somewhat familiar	20 (90.91%)
c. Not familiar at all	0 (0%)
2. After entering through the main gate, which direction do you choose to approach the scripture hall?	
a. Enter clockwise (rightward rotation)	20 (90.91%)
b. Enter counterclockwise (leftward rotation)	2 (9.09%)
3. Do you pause at the prayer wheel path?	
a. Pause and perform simple ritual actions (touching sutra pillars)	20 (90.91%)
b. Pass through quickly without stopping	2 (9.09%)
4. Do you stop at the worship area in front of Buddha statues in the rear hall?	
a. Stay for a period and perform simple blessing rituals	6 (27.27%)
b. Stay briefly to observe surroundings	16 (72.73%)
c. Pass through quickly without stopping	0 (0%)
5. Do you linger around the Buddha statue area in the rear hall?	
a. Yes, walk clockwise around the area	16 (72.73%)
b. Yes, walk counterclockwise around the area	4 (18.18%)
c. Yes, stand still within the area	2 (9.09%)
d. No, exit directly without entering	0 (0%)
6. Do you enter the outer corridor of the rear hall for scripture chanting?	
a. Yes, enter and walk clockwise	12 (54.55%)
b. Yes, enter and walk counterclockwise	2 (9.09%)
c. No, do not enter	8 (36.36%)
7. What factors influence your experience/behavior in this architectural space? (Multiple answers)	
a. Architectural layout and path guidance	14 (63.64%)
b. Religious symbols and environmental atmosphere	12 (54.55%)
c. Religious knowledge and personal interest	8 (36.36%)
d. Following others' actions	4 (18.18%)

others' actions. The statistical data strongly aligns with visitors' spontaneous route preferences and ritual engagement patterns in the Main Hall.

The analysis of actual visitor behavior showed significant consistency with simulated crowd movement predictions, particularly in clockwise circumambulation tendencies at the prayer wheel path and rear hall outer corridor. This validates the use of simulation-based quantitative methods for evaluating the ritual-spatial design of Meidaizhao Mahavira Hall.

Simulation process. Preparations for modeling: Collect the actual environment information and model the building environment in Anylogic platform based on the floor plan of Mahavira Hall; set the basic parameters of the agent-based pedestrians; set the attraction points in each scene area and the target lines at the entrances and exits.

Logical Flow 1-A. Pedestrian agents walk freely within the modeling space and set their probability of choosing each route in the hall equally. Attractors are evenly distributed in each area of the building, and the attractor type settings are selected randomly with the equal delay time.

Logical Flow 1-B. The agent behavior and movement are scripted according to the ritual procedures and routes of the selected case. Using the Prayer Dharma Assembly at the Meidaizhao Monastery as an example, the process of pedestrian agents performing the
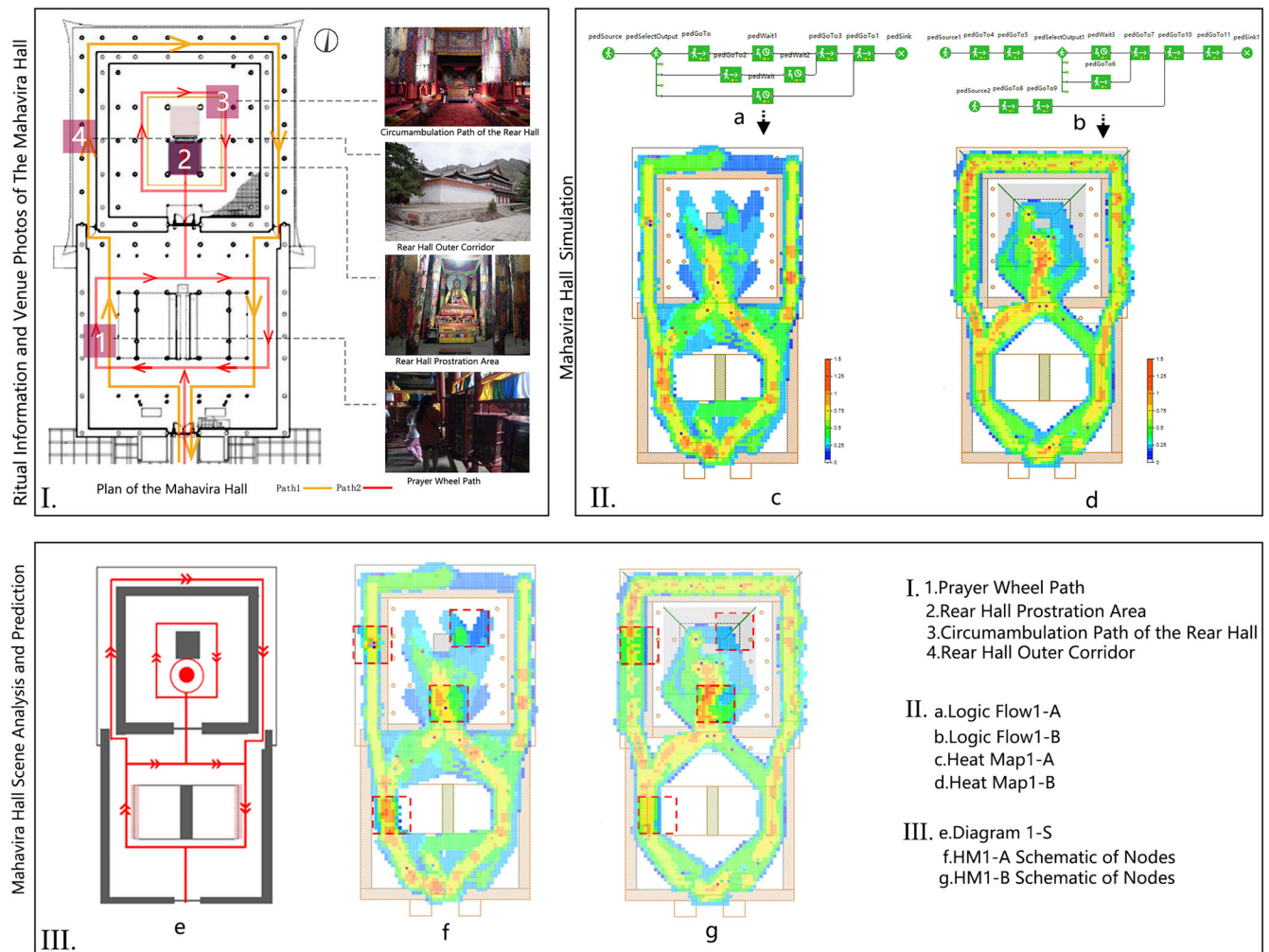
Fig. 3 | Case 1 analytical chart. I Ritual information and venue photos of the Meidaizhao Mahavira Hall. **II** Visualization of the Meidaizhao Mahavira Hall simulation. **III** Comparative analysis between schematic diagrams and simulation results of the Meidaizhao Mahavira Hall. Modified from Zhang[41]. Photographs by the author.

circumambulation ritual is programmed. The path and rectangular nodes from the process modeling library are used to mark spatial waypoints, determining the routes the agents follow upon entering the Buddha hall.

Generating results. HM1-A, HM1-B, Diagram 1-S (Fig. 3).

Analytical process. Table 5, Table 6.

Evaluation conclusions. By combining the quantitative results of the simulation with the analytical judgment, an evaluation of the Ritual Environment of the Meidaizhao Mahavira Hall is made. The space of the main hall contains opportunities for the ritual behaviors of the prayer wheel and worshiping statue. The overall architectural environment of the Buddhist temple matches the ritual activities of the blessing ceremony to a high degree. It is found that the rear hall worshiping area has a disciplinary effect on pedestrians. This disciplinary function is achieved through the spatial layout of the Buddhism space and the arrangement of religious facilities, and effectively promote the occurrence of the Prayer Dharma Assembly within the hall.

Temple of Heaven Huanqiu Altar Complex
The Temple of Heaven is a dedicated venue for the emperor to hold Large Sacrifice. The rituals are held at the winter solstice and the first month of spring every year. The main buildings of the Temple of Heaven are concentrated on the north-south axis of the inner altar. The Huanqiu Altar complex in the south is the place where the emperor worshiped the heaven during the winter solstice[32].

Ritual Flow of Qing Dynasty Emperor's Heaven Worship: The Emperor set out from the palace. Ceremonial procession, after passing through the Meridian Gate, proceeded southward along the central axis to reach the Temple of Heaven. They entered it through the southernmost gate of the western wall. Upon reaching the south gate of the inner wall, the emperor got off the imperial carriage. The emperor then walked to the Imperial Vault to burn incense and performed the ritual of three kneels and nine prostrations. Afterward, he proceeded to the Divine Warehouse to examine the ceremonial vessels and to the Divine Kitchen to check on the sacrificial animals. Finally, the Emperor returned to the Palace of Abstinence for fasting[33].

Spatial nodes of ritual occurrence. Stone Archway, Zhaoheng Gate, Vesting Platform, Imperial Vault, Huanqiu Altar.

Simulation process. Preparations for modeling: On-site research combined with the collation of ancient documents to obtain information on the spatial environment of the case and information on the rituals of sacrificing to heaven. In Anylogic platform, we take part of the plan of the Temple of Heaven Huanqiu Altar as the base map, use the model library to model and set up the paths; the agent-based generating points are arranged at the Huanqiu Altar gate and the Hall of Abstinenc.

Table 5 | Case 1 Heat Map Representation

Nodal space	Ritualistic behavior	HM1-A	HM1-B	Degree of environment-behavior match
Prayer Wheel Path	touch a Buddhist stone pillar	High pedestrian density and slight clockwise trend of pedestrian flow	Pedestrians follow the "right-turning" ritual; believers touch the "prayer wheels" while pass through the path	high
Rear Hall Prostration Area	worship Buddha	Obvious gathering of the pedestrians, indicating good spatial accessibility	The space is highly congregated, and it is a Buddha worship space, where believers perform the kowtow ritual	high
Circumambulation Path of the Rear Hall	worship Buddha	The heat map reveals an irregular, dispersed shape, indicating sparse pedestrian flow	The heat map shows a bracketed shape. Here, pedestrians follow the ritual custom and perform the circling prayer	low
Rear Hall Outer Corridor	chant the sutras	Pedestrians can walk smoothly on both sides of the corridor, and the space behind the corridor is quiet.	Pedestrians follow a clockwise path, rotating to pray and chant	average

Table 6 | Case 1 Environmental Evaluation Analysis

Criteria	Analysis Basis	Analysis Procedure	Conclusion
Crit. i	simulation process	In the Prayer Wheel Path, the Rear Hall Prostration Area and the outer corridor area, the gathering states of pedestrians in the two logical flows tend to be consistent, and their routes are highly overlapped.	Contains opportunities for the act of turning the sutra block and kneeling to the Buddha statue to occur.
Crit. ii	HM1-A, HM1-B	Table 3 shows the performance of each ritual space node of Case 1 in the heat map under different simulation scenarios.	Two of the four node spaces had a high degree of match, one had a low degree, and one had a average degree.
Crit. iii	HM1-A, Diagram 1-S	1. The flow of pedestrians in the back hall is concentrated around the Buddha statue and the altar; 2. The worship area in front of the Buddha statue has the highest pedestrian density and pedestrians stay there for a relatively long time; 3. The worship area is in the center of the main hall, offering high accessibility; 4. The Buddhism space is defined by the placement of a large Buddha statue and the altar.	The Rear Hall Prostration Area has a disciplinary influence on pedestrians. Mechanism: Layout of the rear hall and arrangement of religious ritual facilities.
Crit. iv	Crit. iii Conclusion, Scene Photographs	1. The construction of the Mahavira Hall is closely related to the blessing and worship ceremony; 2. The layout plan, location of the Buddha statue and the paths within the hall are effectively organized; 3. Tibetan Buddhist spaces possess unique place characteristics.	The space of the main hall will affect the consciousness and behavior patterns of believers, guiding pedestrians to perform acts of worship, right-turning and so on. It has a positive effect on the blessing ceremony.

Logical Flow 2-A. Agent generation points are set at Huanqiu altar gate and Hall of Abstinence, editing feasible paths in the spatial environment. Agent pedestrians randomly select routes with random selection probability settings.

Logical Flow 2-B. The ritual actions of the emperor and officials (including the number of bows and the sequence of offerings) as well as the ceremonial route were strictly regulated by the Ministry of Rites. This setting does not take into account the timeline (the day before/ on the day of the ritual), but only simulates the path of the ritual. The gate of the Huanqiu Altar- Zhaoheng Gate- Vesting Platform- Divine Warehouse or Divine Kitchen- Palace of Abstinence- Huanqiu Altar-the End.

Generating results. HM2-A, HM2-B, Diagram 2-S (Fig. 4).

Analytical process. (Table 7, Table 8).

Evaluation conclusions. The environment of Huanqiu Altar complex contains the opportunity of worshiping in Huanqiu Altar and other sacrificial sites; the route organization matches with the flow of the ceremonial procession. It is found that the space of the complex has a disciplinary effect on pedestrians. This disciplining function is achieved

through the effective organization of paths within the grounds and the variation in architectural scale. And it helps create a sacred atmosphere for heavenly worship and facilitates the performance of the rituals to a certain extent. The feudal dynasty system imposed profound constraints and influences on the spatial design of the Temple of Heaven architectural complex. As a spatial vessel for the Heaven worship ceremony, the design core of the Huanqiu Altar complex lies in embedding the ideology of the divine right of kings through ritual regulations. For instance, this is reflected in the strictly controlled architectural hierarchy and orientation settings.

Neixiang County Yamen

Neixiang County Yamen was the county-level administrative office during the feudal period. It had the responsibilities of implementing central policies, maintaining local order, judicial trials, military defense, as well as conducting politically significant ritual activities.

The process of inauguration ritual for local officials: after entering the government office, they first went to the Official's Guardian Temple and the Tudi Temple to worship. Next, the officials would proceed to the Ceremonial Gate, and kowtowed to the Ceremonial Gate in the way of "one kneel and three kowtows". Then the local officials entered the main courtyard, followed the stone - paved path along the main axis, passed through the "Jie Shi Archway", ascended the Moon Platform, and kowtowed to the north to

thank the emperor for his grace. Afterward, the officials would perform a kowtow to the official seal and receive it. Finally, they turned around and paid homage to their peers and subordinates, and the ceremony ended[34].

Spatial nodes of ritual occurrence. The Official's Guardian Temple, the Tudi Temple, the Ceremonial Gate, the Stone Archway, and the Moon Platform.
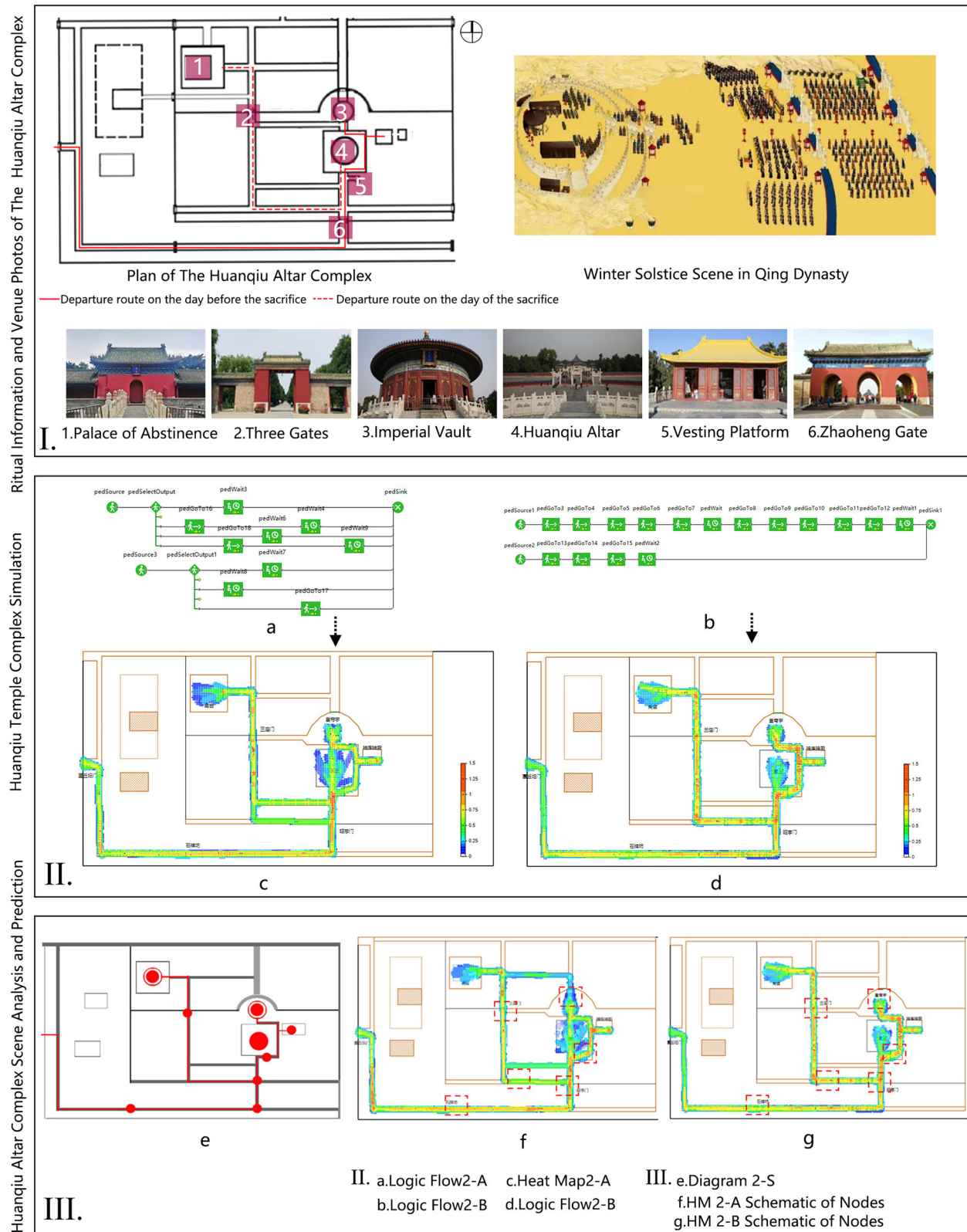

Fig. 4 | Case 2 analytical chart. I Ritual information and venue photos of the Huanqiu Altar Complex. **II** Visualization of the Huanqiu Altar Complex simulation. **III** Comparative analysis between schematic diagrams and simulation results of the Huanqiu Altar Complex. Retrieved from the Web[53].

Table 7 | Case 2 Heat Map Representation

Nodal space	Ritualistic behavior	HM2-A	HM2-B	Degree of environment-behavior match
Stone Archway to Zhaoheng Gate	ceremonial travel	Compared with the section from the entrance to Stone Archway, the pedestrian flow in this section is more densely distributed, and the average speed of pedestrian flow slows down	The node of the Stone Archway is a threshold space. The ritual procession reaches the south gate of the inner level of the Temple of Heaven, and then the emperor gets off the imperial carriage	high
Vesting Platform	dress	Higher density of pedestrian flow, obvious phenomenon of stagnation, higher frequency of use of nearby roads	The emperor goes to the Vesting Platform to change his clothes, and then walked to the Imperial Vault of Heaven to burn incense	high
Zhaoheng Gate to Three Gates	ceremonial travel	Two walking routes occur in the free walking premise; the density of pedestrian flow increases at the Three Gates	The average pace of the ritual procession in this section is slowed down and the flow of pedestrian is evenly distributed.	low
Imperial Vault and Huanqiu Altar	worship	The important ritual space of the Temple of Heaven has a high degree of crowd, the stagnation is evident.	On the day of the ceremony, he went from the Palace of Abstinence to the Huanqiu Altar to heaven worship.	high

Table 8 | Case 2 Environmental Evaluation Analysis

Criteria	Analysis Basis	Analysis Procedure	Conclusion
Crit. i	simulation process	1. At the agent generation point of the Huanqiu Altar Gate, pedestrians are highly likely to choose the path of the south corridor. 2. At the Palace of Abstinence generation point, pedestrians are more likely to choose to go south through the three gates and enter the Huanqiu Altar.	Contains opportunities for the act of worship to take place with reverence for the heavens.
Crit. ii	HM2-A, HM2-B	Table 5 shows the performance of each ritual space node of Case 2 in the heat map under different simulation scenarios.	Three of the four node spaces have a high degree of match and one has a low degree.
Crit. iii	HM2-A, Diagram2-S	1. Pedestrians enter a long corridor from the west gate, slowing down after passing the Stone Archway. 2. When reaching the Vesting platform, the density of pedestrian flow changes greatly and the phenomenon of detention is obvious. 3. The pace of the marching team changes significantly with the space, and the solemn and dignified ceremonial atmosphere is created by slowing down the pace.	The pace of the ceremonial procession is controlled. Thus, the ritual space has a disciplinary effect on pedestrians. Mechanism: The organization of pathway flow and the variation in spatial scale.
Crit. iv	Crit. iii Conclusion, Scene Photographs	1. Worshiping the heaven is the most important ritual in ancient Chinese feudal society. It expresses the ideas of "imperial power is supreme" and "imperial power is granted by heaven" 2. Walking on the long corridor and looking at the spacious buildings of the Temple of Heaven in the distance, the subjects would feel insignificant. Through this, a sense of oppression is generated to highlight the noble and majestic status of the royal family.	The layout creates a physical space imbued with the concept of "heaven-human induction", reflecting a strong ideology of feudal monarchial hierarchy and the ritualistic order of ranks.

Simulation process. Preparations for modeling: Construct the model of Neixiang County Yamen, set the agent parameters, edit the logic flow.

Logic Flow 3-A. Pedestrians randomly select routes with equal choice probability settings.

Logic Flow 3-B. Main Gate- Official's Guardian Temple, Tudi Temple- Ceremonial Gate- Moon Platform- Grand Hall.

Generating results. HM3-A, HM3-B, Diagram 3-S (Fig. 5).

Analytical process. Table 9, Table 10.

Evaluation conclusions. The spatial environment of the county yamen contains the opportunity of bowing behavior; the organization of the path of the building complex matches with the process of the official's inauguration rituals. It shows that the Neixiang County Yamen imposes a disciplining effect on pedestrian movements. This disciplining is achieved through the central axis layout and the connection of courtyards, which provide spatial visual guidance for pedestrians, so their traveling or stopping behaviors occur along the main axis canals.

Tang'an Dong Village
The Dong villages are dominated by stilt houses, while developing some public ceremonial structures. The ritual buildings of the villages clearly express the socio-political structure of the Dong villagers, and the process of construction and use incorporate a variety of Dong rituals, such as drum tower gatherings, sacrifices to the Salma, and antiphonal singing ceremonies, etc.

The Drum Tower is the most symbolic building in the Dong village and is the center of public life, where villagers hold life rites and annual rituals. Elders of the family gather at the Drum Tower and sit around the central fire pit for fire-making ceremonies regularly. Sacrificing 'Sa' is the main religious activity of the Dong villagers, burning incense and paper and offering tea for 'Sa' on the first and fifteenth of each month at the Sasa Altar[35].

Spatial nodes of ritual occurrence. Drum Tower, Theater Pavilion, Courtyard, Sasa Altar.
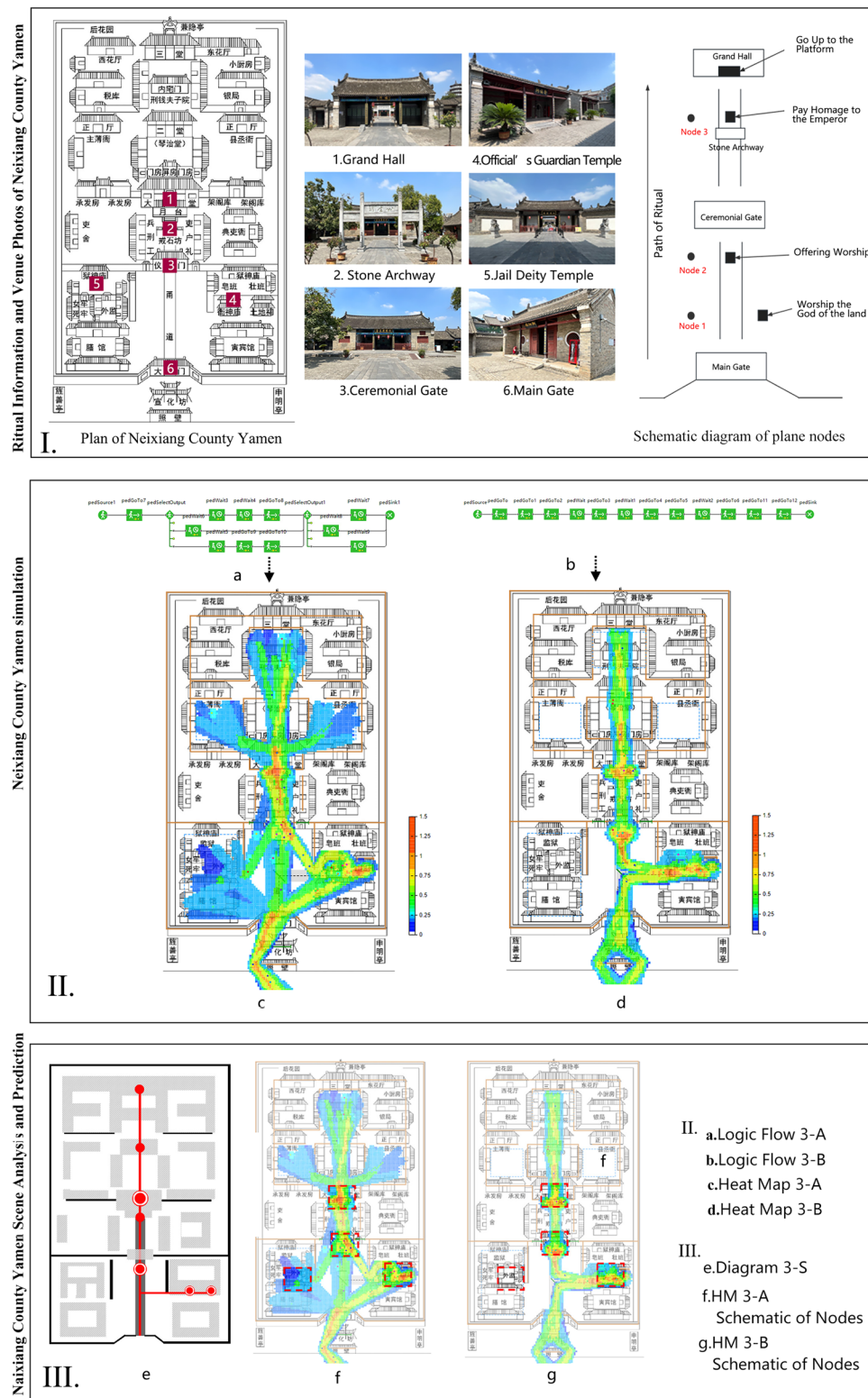
Fig. 5 | Case 3 analytical chart. I Ritual information and venue photos of Neixiang County Yamen. **II** Visualization of Neixiang County Yamen simulation. **III** Comparative analysis between schematic diagrams and simulation results of Neixiang County Yamen. Modified from Liu et al.[43]. Photographs by the author.

Simulation process. Preparations for modeling: Taking the collective ritual activities in Tang'an Dong village as an example, simulate the process and write the logic flows.

Logic Flow 4-A. Pedestrians randomly select routes with equal choice probability settings.

Logic Flow 4-B. Preparation of personnel for drumming and summoning at the Drum Tower, sitting around the fire pit, singing rituals at the theater, and ritual acts at the Sasa Altar.

Generating results. HM4-A, HM4-B, Diagram 4-S (Fig. 6).

Table 9 | Case 3 Heat Map Representation

Nodal space	Ritualistic behavior	HM3-A	HM3-B	Degree of environment-behavior match
Main Axis Walkway	ceremonial travel	Mostly choose the Main Axis Walkway as travel path	Within the symmetrical framework of the plan, the stone - paved path of the main axis becomes the main ceremonial route	average
Official's Guardian Temple and Tudi Temple	worship	High density of pedestrian flow and strong sense of spatial enclosure, showing cohesion	Local officials performed worship ceremonies in the Official's Guardian Temple and the Tudi Temple	high
Ceremonial Gate	kowtow	The Ceremonial Gate serves as a spatial boundary, and the flow of pedestrians is obviously stagnant	Local officials kowtowed to the Ceremonial Gate in the way of "one kneel and three kowtows"	high
Moon Platform	kowtow	Slowdown in the pace of pedestrian flow from the Jie Shi Archway to the Moon Platform	Local officials passed through the Jie Shi Archway, ascended the Moon Platform, and kowtowed to the north to thank the emperor for his grace	high

Table 10 | Case 3 Environmental Evaluation Analysis

Criteria	Analysis Basis	Analysis Procedure	Conclusion
Crit. i	simulation process	1. Routes of the agent pedestrians diverge, with most pedestrians choosing to move forward along the Main Axis Walkway 2. Main axis routes through gates, courtyards and halls, with increased spatial hierarchy or privacy	Contains opportunities for the act of kowtowing to occur.
Crit. ii	HM3-A, HM3-B	Table 7 shows the performance of each ritual space node of Case 3 in the heat map under different simulation scenarios.	Three of the four node spaces had a high degree of match and one had an average degree.
Crit. iii	HM3-A, Diagram3-S	1. The central axis connects the main ceremonial node spaces and the secondary buildings are arranged symmetrically on both sides. 2. The north-south main axis sequence makes the building complex form a unified whole visually, and the flow line is clear 3. Heat map results show the flow of pedestrians slows down in the courtyard and gathers at the gatehouse.	The axial arrangement and spatial layering have a clear disciplining effect on pedestrians, and the doors play a role in defining space. Mechanism: Central axis sequence layout with strong orientation
Crit. iv	Crit. iii Conclusion, scene photographs	1. The ancient ruling class attached importance to the setting up of yamen; the yamen is the most concentrated embodiment of the characteristics of traditional Chinese official architecture. 2. The county yamen strictly adhered to the architectural regulations of "facing south with the main building to the north, civil offices on the left and military offices on the right, administrative halls in front and residential quarters at the rear, and the prison located to the south"[51].	The compositional logic of the spatial order of the county yamen shows the standardization of official architecture and reflects the formal and solemn atmosphere of the political space.

Analytical process. Table 11, Table 12.

Evaluation conclusions. The village environment contains opportunities for villagers' collective behaviors; the spatial pattern of the Dong village matches the villagers' ritual activities. It is found that the planning layout of the village has a certain disciplinary effect on the villagers, and the arrangement of public ceremonial buildings is conducive to villagers' full use of the village space and resources.

pottery workshop
The traditional process of pottery making includes: preparing clay for refining, creating billets for modeling, drying the billets, painting and engraving, and loading the kiln for firing[21]. According to the production process, the space required for operations is divided into specific zones. The preparation of clay for refining is generally divided into areas in the open space near the workshop building. The drawing and molding of billets, as well as the painting and carving of these billets, are organized according to the sequence of work processes within the workshop. The drying of the billets takes place in a sunny and well-ventilated area between the workshop buildings. Finally, the firing process is conducted in the designated kiln area.

Operating space nodes. Clay preparation area, billet making area, billet drying area, kiln area.

Simulation process. Preparations for modeling: Construct a spatial model for traditional pottery production, with the variable being whether the agents follow the pottery production process to edit the logic flow.

Logic Flow 5-A. Pedestrians randomly select routes with equal probabilities of selection.

Logic Flow 5-B. Follow the sequence of process steps.

Generating results. HM5-A, HM5-B, Diagram 5-S (Fig. 7).

Analytical process. Table 13, Table 14.

Evaluation conclusions. The expression of ritual design within the spatial environment of traditional pottery workshops is relatively lacking; the spatial environment does not contain spontaneous ritual behaviors.
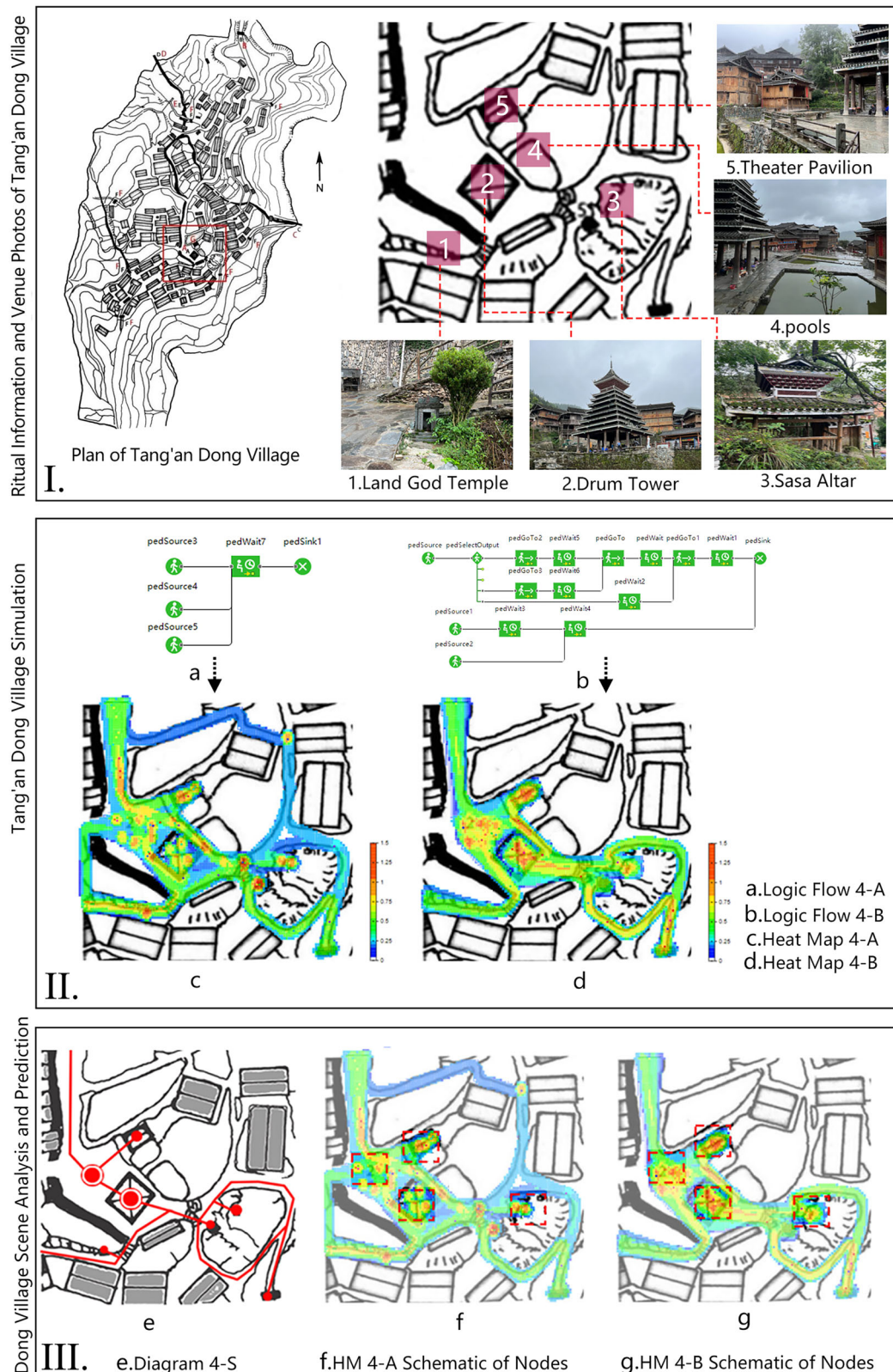
Fig. 6 | Case 4 analytical chart. I Ritual information and venue photos of Tang'an Dong Village. **II** Visualization of Tang'an Dong Village simulation. **III** Comparative analysis between schematic diagrams and simulation results of Tang'an Dong Village. Modified from Jones[54]. Photographs by the author.

Medium-sized lecture hall

Medium-sized lecture halls typically span 300–1000 m² and are suitable for events such as academic conferences, public lectures, and corporate presentations. The hall features a tiered seating arrangement, with rows gradually ascending from the front to the rear to ensure optimal sightlines and acoustic performance. The floor plan follows a longitudinally symmetrical layout, with main entrances positioned at the rear or sides of the hall. The stage is located at the front of the space, while auxiliary facilities such as the control room are situated in the rear section.

Table 11 | Case 4 Heat Map Representation

Nodal space	Ritualistic behavior	HM4-A	HM4-B	Degree of environment-behavior match
Drum Tower	gatherings	Located in the center of the composition, the building is iconic with high pedestrian traffic	The layout of the village is centered on the Drum Tower, which serves the functions of collective deliberation and public entertainment	high
Theater Pavilion	song-singing	Attractive with high foot traffic near ponds	The theater is the stage for performing Dong opera, and the song-singing ceremony takes place here	average
Courtyard	social	The phenomenon of crowd gathering is obvious here, with spatial cohesion	Open space with social and cultural exchange functions; serves as a gathering and dispersal area	average
Sasa Altar	worship	The space is small and there is a noticeable stagnation in pedestrian traffic	A place of worship for the villagers; small spatial scale	high

Table 12 | Case 4 Environmental Evaluation Analysis

Criteria	Analysis Basis	Analysis Procedure	Conclusion
Crit. i	simulation process	1. Pedestrian flows mostly converge at ritual sites such as drum tower, theater and Sasa Altar 2. Folk beliefs have an important influence on traditional village planning. 3. Settlement centers in primitive societies are generally places with public roles and religious ritual symbols[52].	Contains opportunities for villagers to gather and act.
Crit. ii	HM4-A, HM4-B	Table 9 shows the performance of each ritual space node of Case 4 in the heat map under different simulation scenarios.	Two of the four node spaces had a high degree of match and two had a average degree.
Crit. iii	HM4-A, Diagram4-S	1. The drum tower and the small square area have a high density of pedestrian flow. 2. The Drum Tower has high spatial accessibility and architectural iconicity; in case of emergency, the villagers will be summoned by sounding the drum here. 3. The drum tower is the material space center and spiritual culture center of villagers' life.	The central area of village planning attracts pedestrian flow, exerting a disciplinary effect on villagers' public behavior.
Crit. iv	Crit. iii Conclusion, scene photographs	1. In ancient tribal times, villagers lived around public resources (e.g. wells, campfires). 2. Public buildings occupy the center of the village, facilitating efficient use of common resources by villagers.	Mechanism of action: planning layout, road network organization

When organizing an event, the flow of people into the lecture theater needs to be efficient and orderly. The entry process includes the audience signing in at the entrance - undergoing security checks - being guided to their seats; the speakers preparing in the backstage area - tuning up the equipment - waiting for the stage - going on stage.

Functional areas. Audience Area, Stage Area, Control Room, Backstage Area.

Simulation process. Preparations for modeling: Model the lecture hall and write a logic flow with the variable of whether the crowd follows the lecture theater admission process.

Logic Flow 6-A. Pedestrians randomly select routes with random choice probability settings.

Logic Flow 6-B. Simulation of crowd behavior in a lecture hall during an event's admission.

Generating results. HM6-A, HM6-B (Fig. 8).

Analytical process. (Table 15, Table 16).

Evaluation conclusions. As functional spaces for hosting meetings, lectures, and similar events, lecture halls inherently incorporate behavioral logic flowlines into their layout design. Through simulation experiments and evaluation against ritualistic criteria, the case study was assessed and found to lack effective ritualistic design expression.

Analysis of case simulation results

The heatmap data extracted during the simulation process is analyzed to define the spatial characteristics and attributes of each scenario zone (Table 17). Spaces designed for ritual functions create specific ritual spaces through architectural environmental factors (e.g., layout, pathways, scale). These ritual spaces are then endowed with unique place meaning through the execution of ritual processes (e.g., norms, sequences, doctrines). Effective ritual design in architecture relies on the combined interaction of spatial environments and institutional rules. The evaluation of ritual design in architecture is essentially about assessing whether it successfully creates the triggering conditions for ritual behaviors within the space and achieves the effect of enhancing users' perceptual experience.

A reasonable evaluation system should be founded on clear judgment objectives, operable evaluation tools, scientific evaluation indices, and good adaptability. The objective of this study is to evaluate the environmental design of ritual architectural venues. The evaluation tool employed is a simulation process based on AnyLogic platform. The evaluation index focuses on determining whether the architectural environment is useful for triggering ceremonial behaviors and supports the ceremonial process, as perceived by the users of the space, in conjunction with the results of the simulation experiments (Fig. 9).

The validation results from the aforementioned cases demonstrate that all positive cases (ritual spaces) received positive ritual design evaluations
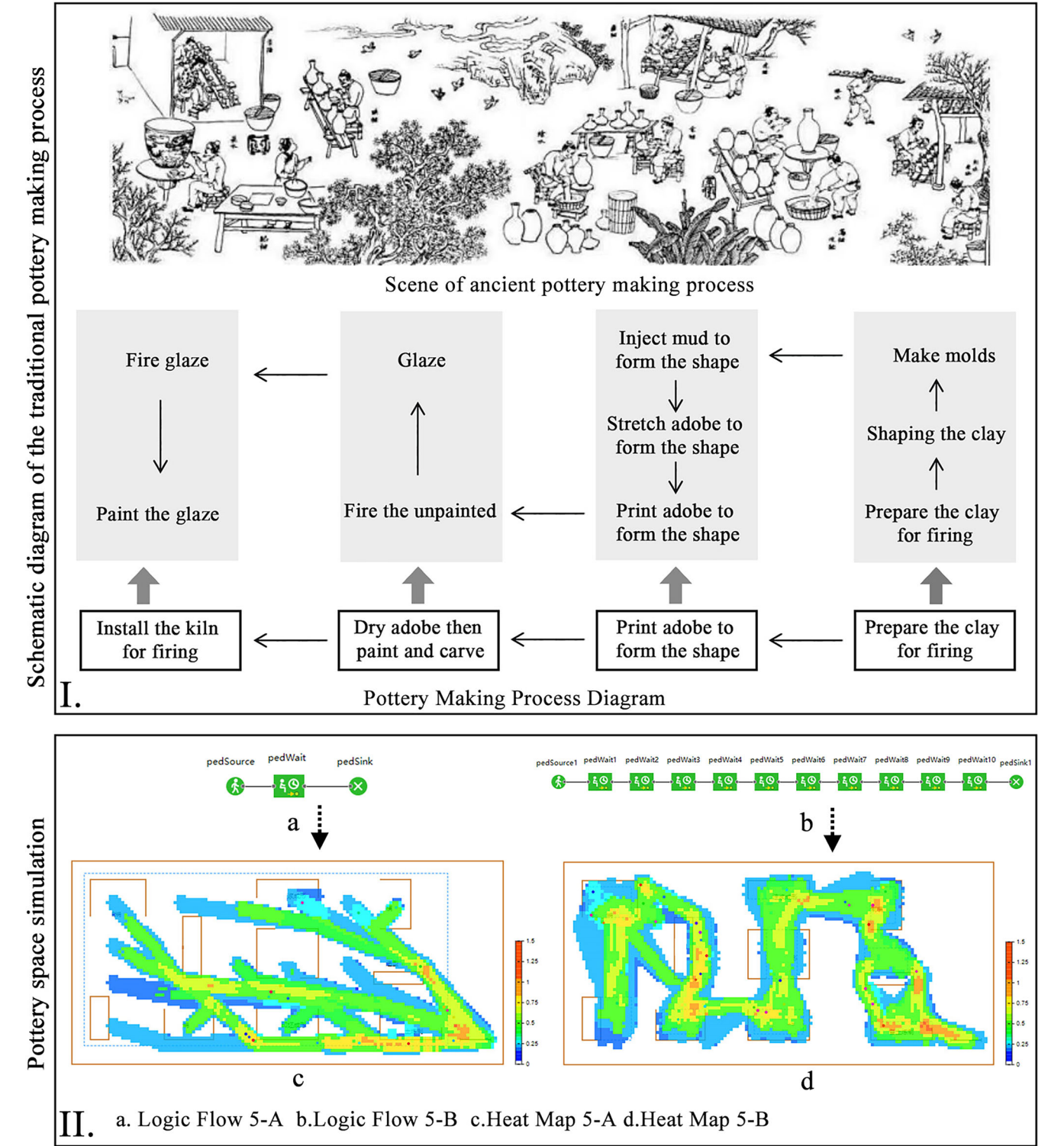
Fig. 7 | Case 5 analytical chart. I Schematic diagram of the traditional pottery making process. II. Visualization of pottery workshop simulation. Retrieved from the Web[55].

Table 13 | Case 5 Heat Map Representation

Nodal space	Ritualistic behavior	HM5-A	HM5-B	Degree of environment-behavior match
Clay preparation area, billet making area, billet drying area, kiln area	traditional pottery	The flow of people is more dispersed, and pedestrian routes are random and disorganized	Pedestrian movement follows the traditional pottery-making process route, forming clusters at operational nodes	low

Table 14 | Case 5 Environmental Evaluation Analysis

| Criteria	Analysis Basis	Analysis Procedure	Conclusion
Crit. i Crit. ii Crit. iii Crit. iv	simulation process, HM5-A, HM5-B, Diagram5-S	The discrepancy between the actual information and the modeled data is obvious, and the pottery production space exhibits spatial disorder.	Does not contain opportunities for fixed behaviors to occur; the spatial environment does not have a disciplinary effect; and does not meet the requirements for ritualistic environmental design expression.
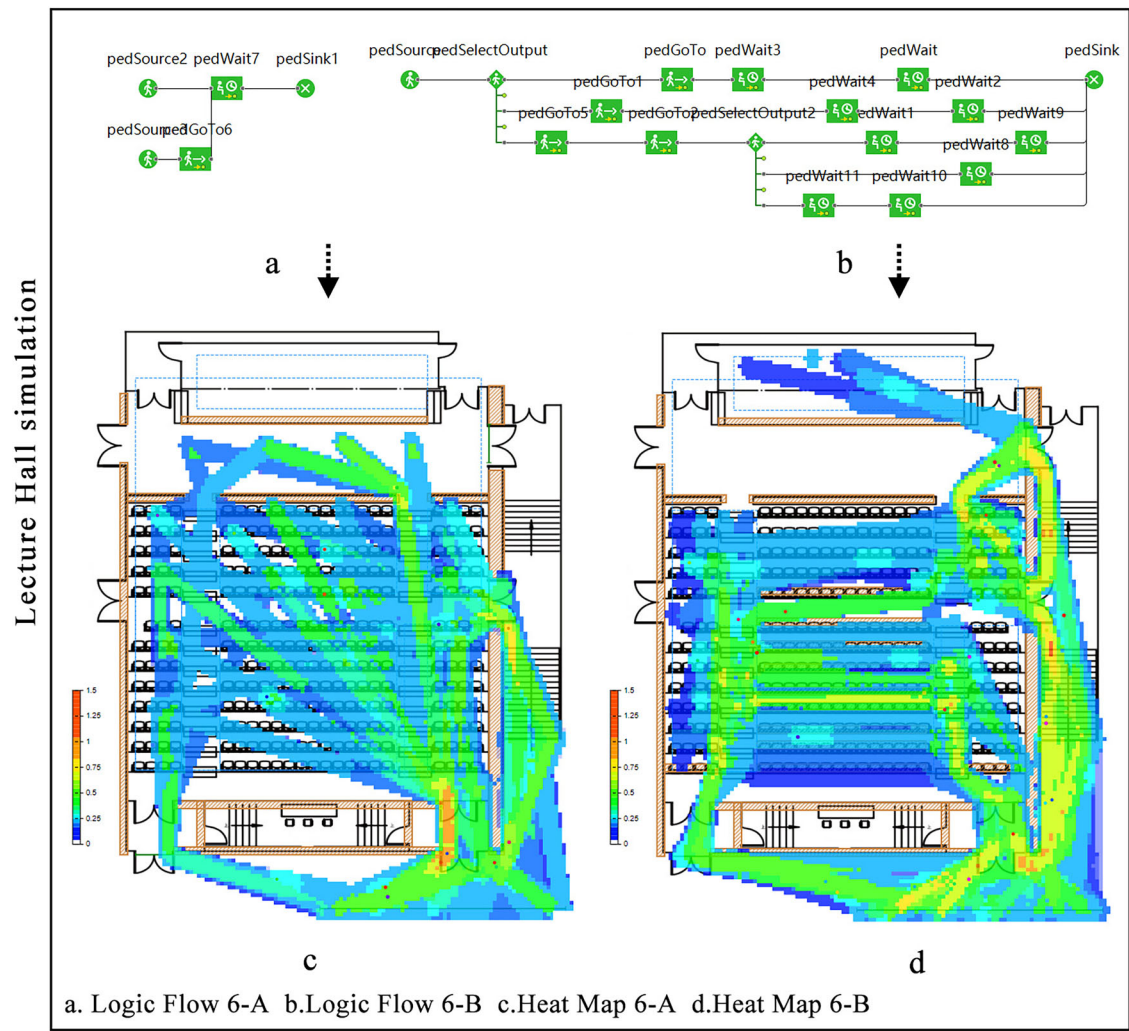
Fig. 8 | Case 6 analytical chart. Visualization of a medium-sized lecture hall simulation.

Table 15 | Case 6 Heat Map Representation

Functional areas	Ritualistic behavior	HM6-A	HM6-B	Degree of environment-behavior match
Audience Area, Stage Area, Control Room, Backstage Area	Event Entry Process	Crowds show a spreading pattern, with stagnation at the rear entrance to the lobby	Pedestrians enter the hall in an orderly manner according to the entrance guide	low

Table 16 | Case 6 Environmental Evaluation Analysis

Criteria	Analysis Basis	Analysis Procedure	Conclusion
Crit. i Crit. ii Crit. iii Crit. iv	simulation process, HM6-A, HM6-B	The simulation results revealed a significant divergence between the spontaneously generated behavioral trajectories of agent pedestrians and the crowd behavior patterns under fixed procedural controls.	The design of the lecture theater space is insufficient to trigger pedestrians to produce fixed behaviors; it does not meet the requirements for the expression of ceremonial environmental design.

Table 17 | Heat map performance analysis

Heatmap Representation	Agent Behavior	Spatial Environmental Characteristics	Spatial Functional Attributes
Orange and Red Zones	High pedestrian dwell time, dense crowd	Strong spatial enclosure, high capacity for crowd; located on central axis or in central position	Ritual Space: Accommodates specific ritual activities, such as prayer halls, drum towers in Dong villages
Yellow and Green Zones	High pedestrian throughput, even crowd distribution	Good accessibility, high openness; convenient paths, facilitating smooth individual passage and crowd evacuation	Circulation Space: Guides pedestrian flow, such as corridors for chanting, pathways at the Temple of Heaven
Blue and Purple Zones	Low pedestrian dwell time, sparse crowd	High privacy, secluded location, winding paths, tranquil atmosphere	Auxiliary Space: Typically used for storage, rest, etc.

Fig. 9 | Procedure Chart. Schematic workflow for ritual space evaluation system.

based on the established criteria, while negative cases (non-ritual spaces) yielded negative evaluations. These case outcomes fulfill the tool's validity requirements defined in the Methods section, confirming that the evaluation tool possesses spatial typological differentiation capability, produces conclusions consistent with historical evidence, and generates interpretable simulation results regarding spatial design mechanisms. Furthermore, analysis of the four ritual building cases (faith/ceremonial/political/secular) in the evaluation process revealed that their key metrics – including path compliance, behavioral synchronization rate, and space utilization efficiency – were all significantly higher than those of negative cases, thereby verifying the method's universality for diverse ritual scenarios.

Ritualistic environmental features

The effective ritual expression of a ritual building depends on the success of its built environment in supporting and facilitating the occurrence of a specific ritual act assumed by the space. In the instrumental validation phase of this study, a sample of typical cases of ritual architecture was selected for evaluation experiments. Analysis of the simulation results indicates that an effective ritual environment is characterized by orderliness and can exert a disciplinary effect on the users of the space.

Comparative analysis of ritual and non-ritual case simulations reveals that ceremonial venue orderliness manifests at multiple levels, including functional zoning, circulation organization, visual orientation, and spatial perception. The design of architectural spaces characterized by a high degree of orderliness can enhance the efficiency of interactions between individuals and their environment. This improvement allows for more effective allocation of environmental resources and services, ultimately increasing the efficiency of ceremonial activities. The concept of the 'disciplinary space' derives from the ideas of French philosopher Michel Foucault in his book *Discipline and Punish*[36]. According to Foucault, power does not only exist in political institutions or legal systems, but permeates every corner of society, including the space and environment in which people live their daily lives. Through this mechanism of power, society can regulate and control people's behavior, thereby maintaining social order.

In the ritual case simulations, we discovered that the ritual spatial environment also embodies this concept of discipline. The form of disciplinary effect within architectural spaces is that the environmental design implies and guides pedestrians' behavioral patterns, thought processes, and even identities, resulting in the development of inherent behavioral tendencies as pedestrians repeatedly experience the same environment, which in turn fosters the emergence of specific ceremonial behaviors and their enduring transmission. The case study reveals that the mechanisms through

which the spatial environment generates discipline primarily include the planning and layout of public spaces, the adjustment of the physical environment, the symbolic communication of teachings, and the creation of an appropriate ambience.

The ritual design expression within the environment subconsciously influences the perceptions and behavioral experiences of its users. Therefore, the factors that affect the ritual expression of the built environment are crucial elements to examine in the design evaluation tool.

Ritualistic Expressions in Traditional Chinese Architecture

Ancient Chinese ceremonies are intricately connected to a rich historical and cultural background. Traditional ceremonial activities are characterized by a strong emphasis on ritual norms, programmed ceremonial processes, strong religious overtones, and the involvement of a diverse range of participants. Consequently, ancient China placed great importance on the design and expression of traditional ritual architectural spaces. Building on the conclusions drawn from the simulation of the positive cases, the typical design methods observed in the cases are summarized, and the universal design principles of traditional Chinese ritual architecture are outlined.

Meidaizhao Mahavira Hall. The architectural design principles of traditional Chinese Buddhist temples are profoundly influenced by religious teachings. The simulation process demonstrates that the arrangement of Buddhist facilities affects pedestrians' perceptions of the spatial environment, encouraging them to linger or gather. Buddhist elements, such as Buddha statues and scripture halls, serve specific functions and carry symbolic meanings. Their thoughtful placement within the architectural environment is crucial for educating believers and disseminating the Dharma.

Temple of Heaven Complex. Ancient China emphasized the concept of the unity between humanity and heaven, striving for harmony between people and nature. This philosophy influenced the architectural environment, often fostering an atmosphere of "obedience to heaven". In the simulation predictions presented, the intentional design of the pathway leading to the Huanqiu Altar Complex effectively regulates pedestrian movement. As individuals approach the site of heaven worship, their pace slows, contributing to the creation of a grand and majestic atmosphere.

Neixiang County Yamen. The official building serves as a representation of ancient power, reflecting a strict social order and hierarchy. The case of the county yamen features a symmetrical layout centered around a central axis and a courtyard arrangement. Symbolic structures, such as

stone archways and ceremonial gates, are positioned along this axis, serving as focal points for visual emphasis. The simulation results presented indicate that pedestrians are inclined to move along the axis, with the sense of ceremony gradually increasing from the outer to the inner areas.

Tang'an Dong Village. The planning and design of traditional villages inhabited by Chinese ethnic minorities are profoundly influenced by the clan system. The village environment reflects unique cultural practices and secular ceremonial activities. The simulation results for the Dong village presented indicate that the space utilization rate of public spaces within the village is extremely high, with pedestrians tending to congregate in the central area of the village, where transportation is well developed. Ancestral halls, temples, theaters, and other buildings are strategically arranged in the village center to foster a communal ritual environment for the villagers.

Based on the discussion above, the universal design principles of traditional Chinese ritual architecture can be summarized as follows: 1). the unity of functionality and symbolism; 2). adherence to the concept of harmonious coexistence between humanity and nature; 3). an emphasis on spatial sequences and axial layouts; and 4). respect for the socio-cultural background of the service group.

Discussion

Ritual, as a complement to social mechanisms, is integral to human life. Ceremonial architecture, serving as a spatial medium for ritual behavior, encompasses not only the existence of physical structures but also embodies collective memory and spiritual aspirations. Its significance is undeniable. The spatial environment of ritual buildings directly influences the quality of participants' ceremonial experiences, making it essential to explore and analyze the expression of environmental ceremonial design.

This study reconsiders the sensory experiences of ritual participants through the lens of human-environment interaction and establishes a quantitative evaluation tool for spatial environments. This tool is applicable to individual ritual buildings or building complexes, as well as their surrounding spaces. The evaluation sample should have a clearly defined functional purpose for conducting the ritual process, a specific scope of spatial environment, and a consistent group of ritual participants.

Existing methods for evaluating the designability of spatial environments include two main categories: empirical observational analysis and subjective perception assessment[37–40]. Empirical observational techniques include video tracking, behavioral trajectory big data, and space syntax analysis, while subjective evaluation methods encompass questionnaires, interviews, and eye-tracking experiments. Compared to traditional architectural design evaluation approaches, the simulation-driven evaluation tool and operational workflow developed in this study offer the following unique advantages: 1) Traditional ritual buildings often lack high-frequency usage data from contemporary users. Simulation experiments can reconstruct ritual scenarios that have either disappeared or occur infrequently, such as the imperial heaven-worship ceremonies at the Temple of Heaven in Beijing. 2) The designed simulation experiment employs a comparative analysis of logic flows (Logic n-A and Logic n-B) to distinctly differentiate between "spontaneous behavior" and "environmentally guided behavior," thereby revealing causal relationships between spatial design elements and pedestrian behavioral patterns. 3) The tool leverages heatmap-based visualization analysis, preserving the graphical traditions of architectural spatial research. Simultaneously, the dynamic multi-dimensional visualization of agent behavior patterns—such as crowd gathering/dispersal and movement trajectory trends—vividly demonstrates how spatial environmental design shapes ritual behaviors.

The application of evaluation tools in design holds significant importance for several reasons: 1) It facilitates the enhancement of architectural design quality, with evaluation feedback guiding the environmental design of ceremonial spaces; 2) It improves the use experience within the space,

increasing both comfort and satisfaction for users; 3) It enhances the sustainability of buildings, promoting a positive cycle between design theory and practice; 4) Evaluating historically and culturally significant buildings aids in the protection of cultural heritage; and 5) The assessment criteria for environmental design in ritual contexts can provide a foundation for developing principles of ritual architecture design and assist in making informed design decisions.

This study has some limitations. First, in terms of the selected technical tools, the advantage of the social force model lies in its ability to provide a relatively simple method for simulating complex pedestrian flow phenomena and its predictive capability. However, its limitation is that it assumes all pedestrians exhibit similar behavioral characteristics, whereas in real-world scenarios, individual differences may influence overall behavior to some extent. Therefore, subsequent research needs to incorporate other models or methods to supplement and refine the simulation results.

Second, in terms of establishing the evaluation process, the assessment relies heavily on qualitative visual comparisons and judgments of simulation heatmaps, which may introduce subjective factors and weaken the persuasiveness of the results. Subsequent research should consider implementing a quantitative scoring system to enhance the rationality and accuracy of the evaluation conclusions through a more precise scoring model.

Additionally, in terms of sample cases, the study primarily focuses on traditional Chinese architecture as the main learning cases, lacking typical Western ritual architecture and contemporary ritual spaces. Future validation research should expand the sample size to include a wider variety of building types, in order to further verify the universality of the tool. In future research, we will conduct real-time tracking and continuous data recording of ritual activities in the case studies, while also delving into the family backgrounds and traditional cultures of specific ritual participants, to further enhance the accuracy and sustainability of the evaluation tool.

With the development and widespread adoption of simulation and modeling technology in architecture, we have discovered that simulating human behavior in relation to the environment, based on the social force model, can serve as both a criterion for evaluation and a design tool. This approach aids in the validation, expression, and decision-making processes regarding spatial-environmental rituals in architect. Therefore, this study is based on the perspective of the user's feeling of the environment, with the help of pedestrian simulation technology, it simulates and analyzes individual behavioral performance in specific environments; combining with the factors that influence the occurrence of ritual behaviors, the study clarifies the criteria for evaluating ceremonial design and constructing a kind of evaluation system. Traditional Chinese architecture, widely regarded as the most explicit carrier of ritual space, was chosen as a case sample to validate the effectiveness of the evaluation tool. The test results from both forward and reverse case samples demonstrate the tool's validity and universality.

In the discussion, the following conclusions were obtained:

1. It is clarified that the main characteristics of a ceremonial environment are order and discipline. The spatial environment exerts a disciplinary effect on pedestrians through mechanisms such as layout creation, path organization, form regulation, and atmospheric rendering.
2. Summarizes the design ideas of ancient China regarding the expression of ceremonial environment, such as the unity of architectural functionality and symbolism, the significance of spatial layout sequence and orientation, the emphasis on harmonious symbiosis with the natural environment, and the consideration of the target population class and other design concepts, which provides inspiration and reference for the design of modern ceremonial spaces.
3. Definition the scope of application for the evaluation tool is the space of architectural venues with ceremonial activities. Its significance lies in its ability to enhance the quality of architectural design, improve the user experience within these spaces, promote architectural sustainability, and protect cultural heritage. Furthermore, the quantitative evaluation of ceremonial environments serves as a valuable foundation for informed decision-making in the design of ceremonial venues.

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The value of this study lies in its establishment of a novel concept for quantitatively evaluating the design expression of the built environment, as opposed to the traditional reliance on subjective qualitative judgments. However, the study still has shortcomings, and in the future, we aim to further integrate the physiological and psychological factors of space users to enhance the application of this simulation and evaluation method.

Data availability

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

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Author contributions

R.Z. proposed a research approach for quantitative evaluation of ritual architectural environments, determined the software to be used in the study, and designed the evaluation tool and process. X.W. took traditional Chinese architecture as examples to validate the effectiveness of the evaluation tool and authored the original manuscript. Q.X. conducted literature reviews and field research on the architectural cases used in the study, and was responsible for the management of this research. Z.W. oversaw the research and reviewed the original manuscript. Q.Z. created the illustrations for the cases analysis and was in charge of the layout of text and images. L.S. organized the research data and verified the research conclusions. Y.Z. contributed to the selection of the research topic and provided the initial research ideas for this study. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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