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CASE STUDY

A comparative study on the spatial vitality of national squares: A visualization analysis based on multi-source data

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Abstract As urbanization advances into its later stages, the need for critical reflection and reform in the design of urban public spaces becomes increasingly important. National squares, as symbolic examples of urban space, serve as vivid indicators of a city's vitality and design characteristics. This research investigates the connection between the vitality representation of squares and vitality construction, aiming to identify strategies for optimizing square design. Using OpenStreetMap trajectory data, remote sensing imagery, and spatial syntax, we analyze these squares at both the urban block and square scales. Our findings reveal four distinct behavioral patterns within these national squares: pausing, interaction, traversing, and boundary crossing. We find that pausing and interaction are closely linked to various vitality construction, such as spatial centripetal force, comfort, safety, aesthetics, and functionality. In contrast, the patterns of passage and boundary crossing are influenced by the permeability of the space and the details of its design. Ultimately, this study offers valuable insights and a scientific foundation for enhancing the vitality of urban square design. By utilizing an expert evaluation system and quantitative data, we establish meaningful connections between design elements and user behaviors, facilitating informed decisions for optimizing square spaces.

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1. Introduction

Urban squares play a crucial role in city life, often serving as venues for important events. However, they frequently encounter challenges such as being overly spacious, underutilized, or lacking vitality. As a special case, national squares embody a strong sense of place, where ongoing interactions between people and space create a dynamic atmosphere (Deng, 2008; Gao, 2010; Wang, 2018; Yang, 2015). Despite the extensive cultural values embedded in such vitality reflect not only cultural values but also highlights concerns when these spaces, however, experience periods of reduced activity, which makes it worth exploring.

The study of urban squares has a long history, dating back to ancient Rome when Marcus Vitruvius Pollio outlined design principles for Roman squares in De Architectura (Pollio et al., 1968). Since then, extensive research has emerged, particularly in Western countries and Japan, where designers like Arata Isozaki (Ching, 2023; Yoshinobu, 1985) and scholars such as Christian Norberg-Schulz and Kevin Lynch have contributed valuable insights into the spirit of place and the humanistic values of public spaces (Lynch, 1984b; Schulz, 1971). Today, national squares are seen as symbols of national pride and design excellence, continually being redesigned to meet evolving economic and social needs. Studies such as Renzhi Hou and Liangyong Wu's "Praise of Tiananmen Square" and Guan Zhaoye's "Optimization and Redesign of Tiananmen Square" remain landmarks in the research on Chinese public squares (Hou and Wu, 1977).

In recent decades, scholars, urban planners, and government agencies have focused on the vitality of urban spaces. However, researchers have long varied over the definition or metrics for measuring vitality. In general, there are two perspectives: the first one is human-centric and follows Jane Jacobs' diversity conditions for urban vitality, focusing on various planning principles with pedestrian flow as a key measure (Maas, 1984); the other is environment-centric and emphasizes the role of the urban environment in facilitating activities (Jin et al., 2017; Long and Huang, 2019; Ravenscroft, 2000; Sung et al., 2013; Sung and Lee, 2015; Wu et al., 2018; Ye et al., 2018; Yue et al., 2017). Some scholars have integrated both approaches, defining urban vitality as a combination of human activities and the physical environment (Fuller and Moore, 2017; Lynch, 1984a). For example, Gehl (2011), in his work *Life between Buildings*, employed qualitative research methods such as case studies and observations to examine the relationship between spatial composition and social interactions. Similarly, Li (1999), in *Introduction to Environmental Behavior Studies*, applied qualitative techniques and psychological theories to explore the interaction between vitality construction and their manifestation in space. Previous studies have shown that qualitative research methods are valuable for gaining a deeper understanding of the underlying mechanisms of spatial vitality. Based on this, this paper systematically reviews vitality indicators from the aforementioned literature.

More recently, with the widespread use of digital information and big data, the study of spatial vitality has shifted from qualitative to quantitative analysis. In 2014, the University of Vermont pioneered the use of computer programs to quantify the livability of urban street views, and this approach has since been extended to other urban spaces. In terms of measurement, in 2016, Ying Long developed an evaluation system by integrating vitality indicators from two distinct schools of thought. This system was built on the concepts of Vitality Representation (B1) and Vitality Construction (B2). To quantify these indicators, data such as assessments of basic spatial elements, street view images, and pedestrian flow analysis were utilized. The results of this system were then validated through expert scoring focused on spatial vitality evaluation (Wu et al., 2018). This evaluation system, supported by the expert validation, laid the groundwork for the framework used in subsequent research papers. By integrating quantitative and qualitative methods, this approach allowed for an objective comparison across different study subjects, uncovering more detailed insights and relationships.

Due to the complexity of public space, there is an increasing tendency to combine quantitative and qualitative research methods. This integrated approach, which incorporates both the physical built environment and subjective perception factors, offers a more comprehensive explanation and better aligns with real-world conditions than single-dimensional methods (Liu et al., 2024; Osunkoya and Partanen, 2024). In the study of national squares, subjective elements such as spatial aesthetics and safety are key to understanding vitality, yet these factors are challenging to measure quantitatively.

Building on prior research, this study introduces a comprehensive framework to analyze the vitality of national squares. It combines numerical data, such as movement patterns from OpenStreetMap (OSM) and spatial configuration metrics, with subjective insights from expert evaluations. Through a comparative approach—merging quantitative findings with qualitative insights from expert scores—this research examines the inherent links between Vitality Representation (B1) and Vitality Construction (B2). By combining both research methods, a more detailed analysis of the relationship between spatial behaviors and physical space composition may be achieved.

In constructing the theoretical framework, this study establishes a three-level evaluation system (B—C—D) to assess spatial vitality in national squares, as detailed in Fig. 1. This system is organized into primary (B1—B2), secondary (C1—C4), and tertiary (D1—D10) indicators, offering a structured approach to analysis. The primary level comprises two main components: Vitality Representation (B1) and Vitality Construction (B2). Vitality Representation (B1) examines observable activities within the space, while Vitality Construction (B2) investigates the environmental factors that sustain these activities. At the secondary level, these components are further elaborated. Under Vitality Representation (B1), Behavior Patterns (C1) and Pedestrian Trajectory (C2) are evaluated using remote sensing imagery and OpenStreetMap trajectories, respectively, to understand crowd dynamics. For Vitality Construction (B2), the

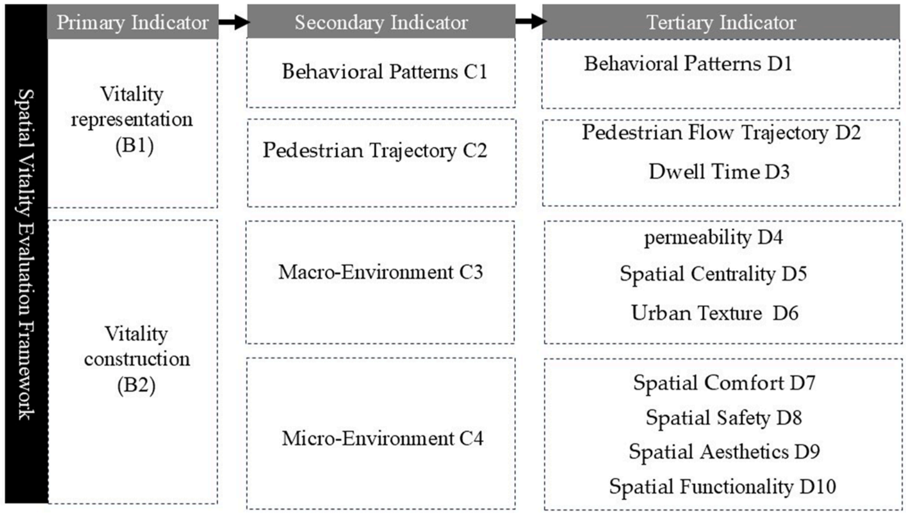

Fig. 1 Spatial vitality evaluation framework.

Macro-environment (C3) and Micro-environment (C4) are analyzed through spatial configuration studies and user feedback, shedding light on how the environment shapes vitality. The tertiary level refines this assessment with specific measures, such as Spatial Permeability (D4) and Spatial Comfort (D7), among others (D1—D10). These detailed indicators enable a comprehensive evaluation of the spatial qualities under investigation. This evaluation system, supported by data analysis, provides a solid foundation for the paper's framework. It facilitates a systematic exploration of spatial vitality in national squares, enhancing insights into the relationship between spatial design and human activity (Chen et al., 2020; Duan et al., 2007; Harvey and Aultman-Hall, 2016; Long and Hao, 2022; Long and Tang, 2019; Maas, 1984; Sheng et al., 2018).

To explore the spatial vitality of national squares universally, this study classifies them into four functional categories: National Memorial Squares, Political and Commercial Center Squares, Transportation Hubs, and Religious and Monumental Squares. These categories reflect the diverse roles that national squares play in urban environments. This study selects seven typical examples from four categories: Tiananmen Square (Beijing), the National Mall (Washington, D.C.), Dam Square (Amsterdam), Trafalgar Square (London), Piazza San Pietro (Vatican City), Place de la Concorde (Paris), and Puerta del Sol (Madrid). By integrating multi-source data, the research cleaned and standardized OpenStreetMap (OSM) trajectory data to ensure reliability and comparability. Additionally, it combined spatial syntax parameters, satellite imagery analysis, and expert scoring to construct a comprehensive database.

Moreover, the research findings cover two levels: the urban block and the square, summarizing four types of Behavioral Patterns (C1) observed within national squares: pausing, interacting, traversing, and boundary crossing. The study delves into the relationship between this Vitality Representation (B1) and Vitality Construction (B2). Drawing from user data and insights from classic national squares, this research offers new scientific perspectives on square space design. The structure of the paper is as demonstrated in Fig. 2.

2. Materials and methods

2.1. Data measurement

2.1.1. Objective assessment indicators (D1—D6)

This study employs multi-source data to analyze the National Square and its surrounding urban area. The data sources include OpenStreetMap (OSM) trajectory data, Points of Interest (POI) data, remote sensing imagery, Google Street View maps, and spatial syntax references (Huang et al., 2019; Pizzolotto, 2022; Tian et al., 2019). Table 1 outlines the data sources for Vitality Representation (B1), covering Behavioral Patterns (D1), Pedestrian Flow Trajectory (D2), and Dwell Time (D3). Similarly, Table 2 details the data sources for Vitality Construction (B2). The analytical data synthesizes 5 expert evaluations, 4384 validated trajectory entries, and a 350 km^2 remote sensing mosaic, with particular emphasis on a 50 km^2 core zone surrounding the square. Spatial syntax modeling was conducted an urban scale (350 km^2) using an integration radius of $R = 300$[1] to assess configurational properties. A cleansed OSM trajectory dataset[2] was systematically processed to quantify individual Dwell Times (D3), Pedestrian Flow Trajectory (D2), and Behavioral Patterns (D1) within the square. To ensure the accuracy and depth of the analysis, this research incorporates prior studies and conducts a comprehensive review of the collected multi-source data.

[1] In space syntax analysis, the parameter $R = 300$ defines a radius of 300 m for evaluating local spatial properties, such as connectivity and accessibility. This distance, roughly corresponding to a typical walking range, is used to study how spatial layouts within a 300-m area impact pedestrian movement and interaction in urban settings.

[2] OSM trajectory data is sourced from GPS tracks uploaded by users worldwide. These data are collected using smartphones, handheld GPS devices, and other mobile technologies. The GPS tracks recorded by users or through tracking applications are then uploaded to the OSM database, contributing to the public data repository.

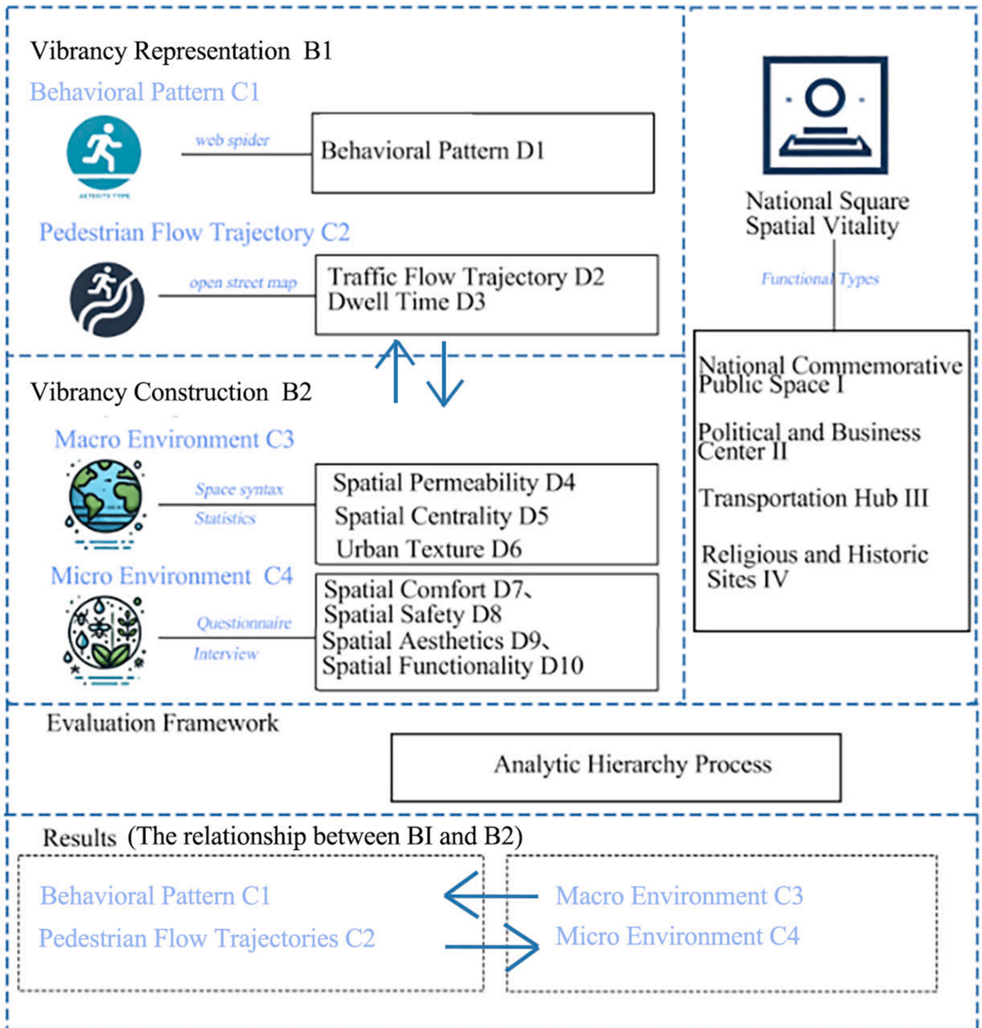

Fig. 2 Research framework.

Table 1 Data collection sources for vitality representation (B1).

Evaluation level	Behavioral patterns (D1)	Pedestrian flow trajectory (D2) and dwell time (D3)
Definition	Crowd behaviors, including pausing, interacting, and traversing.	The pathways and dwell time of pedestrian movement.
Reference basis and data sources	Remote sensing imagery, google street view, and field surveys to assess human activities.	OpenStreetMap (OSM) data, with cleaned and filtered trajectories.

2.1.2. Subjective evaluation metrics (D7—D10)

This study conducted a thorough analysis of the subjective evaluation metrics D7 to D10, applying a combination of field research, geographic information data, and literature review. To enhance the understanding of these metrics, interviews with experts were also conducted. Together, these methods offer comprehensive insights into spatial comfort, safety, aesthetics, and functionality, allowing for a deeper appreciation of how these factors impact user experiences in urban environments.

2.2. Data analysis

2.2.1. Development of evaluation methods for public space vitality

Jan Gehl has emphasized that the vitality of a space is influenced by both its spatial characteristics and the behavior patterns of its users (Gehl, 2011). Currently, there is no standardized metric for measuring vitality. Building on the 2016 study, "Quantitative Evaluation and Analysis of Street Vitality Construction—A Case Study of Chengdu,"

Table 2 Data collection sources for vitality construction (B2).

Evaluation	Evaluation level	Definition	Reference basis and data sources
Macro environment (urban block dimension)	Spatial permeability (D4)	Traversability of square and surrounding blocks	Analysis of spatial syntax's choice and integration
	Spatial centrality (D5)	Ability to attract pedestrian flow	Analysis of spatial syntax's choice and integration level
	Urban texture (D6)	Spatial organizational pattern	Remote sensing imagery
	Spatial comfort (D7)	Physical and psychological comfort	Expert scores, remote sensing imagery.
Micro environment (square dimension)	Spatial safety (D8)	Physical and psychological safety	Remote sensing imagery, OSM trajectories.
	Spatial aesthetics (D9)	Visual quality of architectural and landscape elements	Literature, field surveys, expert scores
	Spatial functionality (D10)	Capacity to support diverse activities	Remote sensing imagery, academic sources

which introduced a domestic exploration into spatial vitality metrics, this research establishes a set of indicators specifically designed to assess the vitality of public squares. These indicators primarily focus on pedestrian movement patterns, behavioral trends, surrounding facilities, and the texture of adjacent roads, all identified as key contributors to vitality (Gehl, 2011; Hillier et al., 2019; Long et al., 2021).

This study employs the three-level indicator framework to evaluate the vitality of national squares. Primary indicators outline the overall objectives, secondary indicators specify detailed dimensions, and tertiary indicators provide concrete, quantifiable measures. To determine the indicator weights, the Analytic Hierarchy Process (AHP) is employed to calculate the weights of the indicators in the vitality evaluation system for squares. A panel of five experts determined the weights for each indicator and the overall ranking. The final evaluation method includes two primary indicators, four secondary indicators, and ten tertiary indicators, as demonstrated (Table 3). The vitality scores for the seven national squares were calculated using a sophisticated weighted function, with the specific formula provided in Equation (1):

$$G = \sum_{i=1}^{n} O_i \times W_i \quad (i = 1, 2, 3, \ldots, n). \tag{1}$$

In this formula, the vitality score (G) is computed as a weighted sum, where O_i represents the score of the i-th indicator and W_i its weight. O_i is derived from multi-source data (e.g., OSM trajectories, expert scores), and Wi is determined by five experts using the AHP method. A higher total score indicates greater vitality of the square.

2.2.2. Expert evaluation scoring

The Analytic Hierarchy Process (AHP) is a mathematical method used for multi-criteria decision analysis. It decomposes complex problems into a hierarchical structure,

Table 3 Indicators of national squares vitality.

Objective layer	Primary indicator	Weight	Secondary indicator	Weight	Tertiary indicator	Weight	Composite weight
Spatial dynamism	Vitality representation (B1)	0.3333	Behavioral patterns (C1)	0.6667	Behavioral patterns (D1)	1	0.222211
			Pedestrian trajectories (C2)	0.3333	Pedestrian flow trajectory (D2)	0.6667	0.09257
					Dwell time D3	0.3333	0.018519
	Vitality construction (B2)	0.6667	Macro-environment (C3)	0.3333	Spatial permeability (D4)	0.2973	0.071152
					Spatial centrality (D5)	0.539	0.123794
					Urban texture (D6)	0.1638	0.020434
			Micro-environment (C4)	0.6667	Spatial comfort (D7)	0.2042	0.070007
					Spatial safety (D8)	0.3458	0.214421
					Spatial aesthetics (D9)	0.2042	0.044152
					Spatial functionality (D10)	0.2458	0.120812

enabling decision-makers to systematically analyze and assign weights across various levels. AHP involves constructing a judgment matrix, which focuses on tertiary indicators to assign weights to secondary and primary indicators. Once these weights are determined, the data can be analyzed to identify and compare variations.

This study employs the Analytic Hierarchy Process (AHP) to determine the weights of ten indicators (D1–D10) based on the evaluations of five experts. The experts scored these indicators according to the functional needs of squares, such as utility and aesthetics, and user behavior priorities, including safety and comfort. For instance, Spatial Safety (D8) received a high weight due to its direct impact on pedestrian experience and square usage. This weighting approach balances objective and subjective factors in fostering square vitality. Using the experts' matrix judgments, the indicators (D1–D10) were assessed, and their respective weights were calculated based on these evaluations. The core steps of the AHP method include the following:

(1) Weight assignment in the evaluation system

To assess the impact of various factors, experts were asked to perform matrix judgments on the evaluation indicators (D1–D10). Based on their evaluations, the corresponding weights were calculated. The detailed effort scale used for this process is as demonstrated (Table 4). While the weighted data cannot be compared using average values, it can be used to analyze variability.

(2) Consistency test of the AHP model

To ensure the reliability of the AHP model, a comprehensive consistency test was conducted on the judgment matrix. This process involved several steps: constructing the judgment matrix, calculating the maximum eigenvalue ($\lambda_{\max}$) and its corresponding eigenvector, determining the Consistency Index (CI), identifying the Random Consistency Index (RI), and calculating the Consistency Ratio (CR).

Table 4 Importance judgments of matrix elements.

Scale	Meaning
1	Two factors compared, having equal importance
3	Two factors compared, the former is slightly more important than the latter
5	Two factors compared, the former is clearly more important than the latter
7	Two factors compared, the former is significantly more important than the latter
9	Two factors compared, the former is extremely more important than the latter
2, 4, 6, 8	Intermediate values between two adjacent judgment factors
Reciprocal of the above values	When two factors are compared in reverse, the reciprocal of the original comparison value is used

The judgment matrix for criteria (D4, D5, D6) was constructed as shown in Equation (2):

$$A = \begin{pmatrix} 1 & 0.5 & 2 \\ 2 & 1 & 3 \\ 0.5 & 0.3333 & 1 \end{pmatrix}. \tag{2}$$

Using the eigenvalue decomposition method, we calculated the maximum eigenvalue, $\lambda_{\max} = 3.0092$. The formula for the CI is provided in Equation (3):

$$CI = \frac{\lambda_{\max} - n}{n-1} = \frac{3.0092 - 3}{3-1} = 0.0046. \tag{3}$$

For a 3×3 judgment matrix, the RI value is 0.58. Consequently, the CR is calculated as follows:

$$CR = \frac{CI}{RI} = \frac{0.0046}{0.58} = 0.0079. \tag{4}$$

Since the CR is less than 0.1, it is considered that the construction of the judgment matrix is reasonable. For (D7, D8, D9, D10), the construction of the judgment matrix is as follows:

$$A = \begin{pmatrix} 1 & 0.5 & 1 & 1 \\ 2 & 1 & 2 & 1 \\ 1 & 0.5 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{pmatrix}. \tag{5}$$

Using the eigenvalue decomposition method, we calculated the maximum eigenvalue, $\lambda_{\max} = 4.0605$. The CI was then calculated using the formula in Equation (6):

$$CI = \frac{\lambda_{\max} - n}{n-1} = \frac{4.0605 - 4}{4-1} = 0.0202. \tag{6}$$

For a 4×4 judgment matrix, the RI value is 0.9. Consequently, the CR is calculated as follows:

$$CR = \frac{CI}{RI} = \frac{0.0202}{0.9} = 0.0224. \tag{7}$$

Since the CR is less than 0.1, the construction of the judgment matrix is considered reasonable.

(3) Expert scoring using the AHP

A composite vitality index was used to evaluate the spatial vitality of the national squares. To ensure both accuracy and professionalism, ten experts with formal architectural backgrounds were invited to participate in the scoring process. Five experts conducted on-site surveys of squares in seven different countries, while the other five used Google Street View and detailed descriptions for their evaluations. The evaluation criteria were divided into five levels—excellent, good, average, below average, and poor—with corresponding scores of 10, 8, 6, 4, and 2, respectively. The scoring system is designed to reflect the vitality levels of the squares, as demonstrated in Table 5.

Table 5 Scoring criteria.

Evaluation factor	Scoring criteria	Score
Qualitative assessment indicators	Excellent	10
	Good	8
	Average	6
	Below average	4
	Poor	2

3. Results and discussion

3.1. Discussion on AHP data results

In the comparative analysis of the expert scoring results for the spatial vitality of national squares, as demonstrated in Table 6 and Fig. 3, the data indicate that the National Mall achieves a high score of 7.4355, reflecting significant spatial vitality. Conversely, Place de la Concorde registers a significantly lower score of 3.9752. This disparity is primarily due to its function as a traffic nexus, which adversely impacts the pedestrian circulation within the square. Additionally, Place de la Concorde has recorded a low score in Spatial Safety (D8). This issue largely stems from the insufficient separation of pedestrian and vehicular pathways, undermining the sense of safety and consequently diminishing the overall rating of the square.

The analysis of standard deviations for different indicators revealed that spatial centrality (standard deviation = 2.41) and dwell time (standard deviation = 2.00) showed the greatest variability in scores. This variation highlights differences in functionality and spatial design across national squares in terms of attracting visitors and accommodating longer stays. Conversely, Spatial Functionality (standard deviation = 0.74) and Spatial Aesthetics (standard deviation = 1.32) exhibited smaller standard deviations and higher scores, indicating greater consistency in evaluations. This consistency may suggest the presence of universal standards or shared objectives in square design.

Additionally, the research underscores the significance of indicators such as spatial behavior patterns, pedestrian trajectories, dwell time, spatial centrality, spatial comfort, and spatial safety. These factors are especially important for comparing and assessing the spatial vitality of national squares.

3.2. Discussion on the mechanisms influencing square space vitality

This chapter, building upon the AHP (Analytic Hierarchy Process) method introduced in the previous chapter,

Table 6 Expert evaluation table.

Total score			National memorial square		Political and commercial center square		Transportation hub		Religious and monumental square
			Tiananmen Square	The National Mall	Puerta del Sol	Dam Square	Place de la Concorde	Trafalgar Square	Saint Peter's Square
Total score			6.2589	7.4355	5.6708	6.0709	3.9752	4.5583	6.7066
	Code	Weight	Indicator score	Indicator score	Indicator score	Indicator score	Indicator score	Indicator score	Indicator score
Primary indicator	Vitality representation B1	0.3333	1.3328	2.1295	1.7498	1.8887	0.6665	1.2221	2.0183
	Vitality construction B2	0.6667	4.9261	5.3060	3.9210	4.1822	3.3087	3.3362	4.6883
Secondary indicator	Behavioral patterns C1	0.6667	0.8884	1.5555	1.1111	1.2222	0.4444	0.8888	1.3333
	Pedestrian trajectory C2	0.3333	0.4444	0.5740	0.6387	0.6665	0.2221	0.3333	0.6850
	Macro-environment C3	0.3333	1.5516	1.6425	1.2893	1.1874	0.7182	0.8722	1.6971
	Micro-environment C4	0.6667	3.3745	3.6635	2.6317	2.9948	2.5905	2.4640	2.9912
Tertiary indicator	Behavioral patterns D1	0.222211	0.8884	1.5555	1.1111	1.2222	0.4444	0.8888	1.3333
	Pedestrian flow trajectory D2	0.0926	0.3703	0.4629	0.5091	0.5554	0.1851	0.2777	0.5554
	Dwell time D3	0.0185	0.0741	0.1111	0.1296	0.1111	0.0370	0.0556	0.1296
	Spatial permeability D4	0.0712	0.3558	0.4269	0.3558	0.3913	0.1779	0.2135	0.4269
	Spatial centrality D5	0.1238	1.1141	1.0522	0.7428	0.6190	0.3714	0.4952	1.0522
	Urban texture D6	0.0272	0.0817	0.1634	0.1907	0.1771	0.16890	0.1635	0.2180
	Spatial comfort D7	0.0700	0.1400	0.4200	0.2800	0.4200	0.3150	0.3500	0.3850
	Spatial safety D8	0.2144	1.9298	1.8226	1.1150	1.2865	1.17932	1.0721	1.2865
	Spatial aesthetics D9	0.0392	0.3140	0.3336	0.2944	0.3218	0.2747	0.1962	0.3532
	Spatial functionality D10	0.1208	0.9907	1.0873	0.9423	0.9665	0.8215	0.8457	0.9665

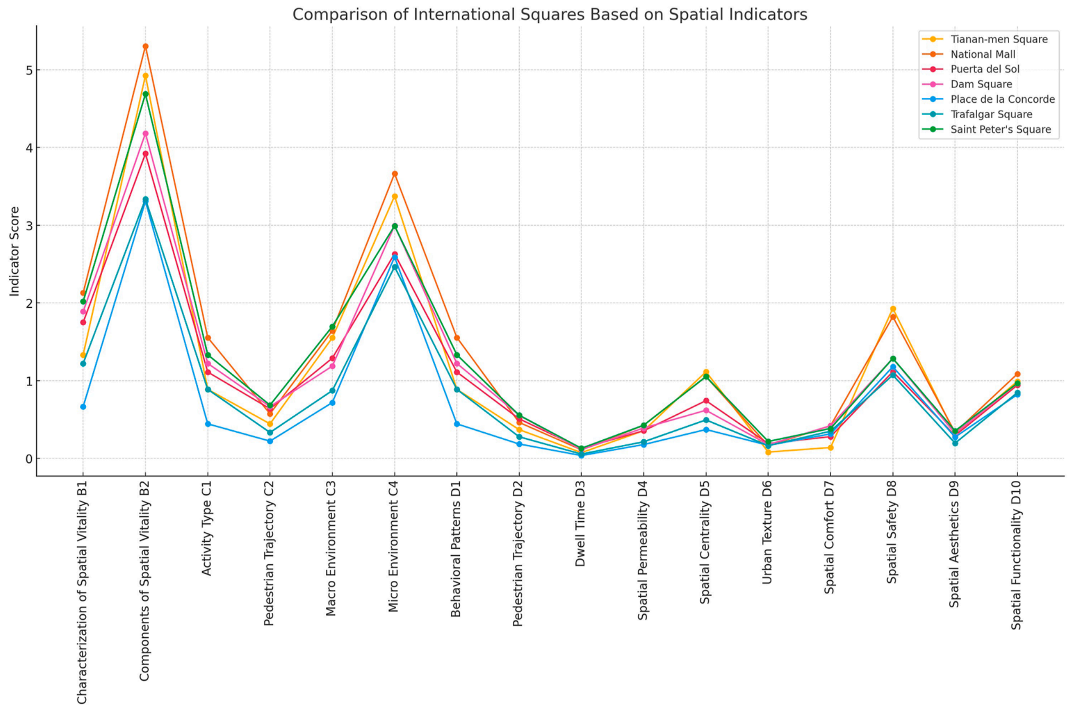

Fig. 3 Comparison of international squares based on spatial indicators.

utilizes multi-source data—including OSM (OpenStreetMap) trajectories, space syntax analysis, remote sensing imagery, and expert evaluations—to examine the vitality characteristics of seven national squares at both urban block and square scales. The research revealed relationships between four distinct Behavioral Patterns (D1)—pausing, interacting, traversing, and boundary crossing—and essential vitality elements, including spatial permeability, comfort, safety, aesthetics, and functionality. Table 7 synthesizes the salient elements of Vitality Representation (B1) and Vitality Construction (B2) across seven national squares, systematically analyzing their inter-dependencies to elucidate how Vitality Construction (B2) influences Vitality Representation (B1). These findings are systematically summarized in Table 7, which integrates each square's Behavioral Patterns (D1), Vitality construction (D4–D10),

Table 7 Relationship analysis of vitality representation (B1) and vitality construction (B2) elements in seven national squares.

Functional classification	Square name	Extracted vitality representation (B1)	Extracted vitality construction (B2)	Relationships analysis B1 between B2
National memorial square	Tiananmen square	Pausing, interacting	Spatial safety (D8): 1.9298; spatial functionality (D10): 0.9907	High spatial safety, functionality, and comfort support pausing and interacting; high permeability promotes traversing.
	The national mall	Pausing, traversing	Spatial comfort (D7): 0.3500; spatial permeability (D4): 0.4269	
Political and commercial center square	Dam square	Interacting, traversing	Spatial functionality (D10): 0.9423; spatial safety (D8): 1.1150	High functionality, aesthetics, and safety enhance interacting and traversing.
	Puerta del Sol	Interacting, traversing	Spatial functionality (D10): 0.9665; spatial aesthetics (D9): 0.3218	
Transportation hub	Place de la Concorde	Traversing	Spatial permeability (D4): 0.1779; spatial aesthetics (D9): 0.2747	High permeability and aesthetics promote traversing; high functionality and aesthetics support interacting.
	Trafalgar Square	Traversing, interacting	Spatial functionality (D10): 0.8457; spatial aesthetics (D9): 0.1962	
Religious and memorial square	Piazza San Pietro	Pausing, interacting	Spatial safety (D8): 1.2865; spatial functionality (D10): 0.9665	High safety and functionality promote pausing and interacting.

and their interrelationships, offering a robust foundation for subsequent analysis.

3.2.1. Results and analysis of vitality representation (B1)

This study investigates the behavioral patterns, pedestrian trajectories, and activity behaviors across seven national squares using OSM trajectory data and satellite street view imagery (Huang et al., 2019). Figure 4 shows the behavioral trajectories within the square, with data extracted from OpenStreetMap and generated using GIS software. The analysis reveals distinct visitor behaviors, which can be categorized into four main types: pausing, interaction, traversing, and boundary crossing. These patterns collectively contribute to the spatial vitality of the squares.

"Pausing" refers to visitors intentionally entering and staying for an extended period; "interaction" involves engaging with others or the environment; "traversing" describes movement along deeper pathways; and "Boundary crossing" captures the tendency to remain near the edges of the squares. An overview of the OSM trajectory maps and the corresponding Behavioral Patterns (C1) is presented in Table 4.

In large spaces like Tiananmen Square and the National Mall, pedestrian density is relatively low, resulting in more singular behavioral patterns. Tiananmen Square primarily showcases pausing behavior, where its monumental architecture fosters a solemn atmosphere, though the expansive layout and lack of resting areas may lead to visitor fatigue (Pizzolotto, 2022). Conversely, the National Mall exhibits a mix of behaviors—pausing, interaction, and traversing—supported by its greenery and strong spatial sequence, making it conducive for daily leisure activities.

Squares with a more relaxed ambiance, such as Dam Square, Trafalgar Square, Concorde Square, and Puerta del Sol, benefit from the presence of rest facilities and nearby food outlets, which promote interaction and Boundary crossing. As shown in Fig. 4, their movement trajectories are more winding, suggesting less directed traffic flow and a tendency toward leisurely exploration, which in turn enhances social interactions. In contrast, smaller squares generally have higher pedestrian density and greater diversity in behavioral patterns, highlighting their unique advantage in facilitating interactions.

Trafalgar and Concorde Squares, functioning as major transportation hubs, exhibit more complex traffic flows with a blend of pedestrian and vehicular pathways. Figure 4 shows that their movement trajectories are more linear, indicating purposeful travel, shorter dwell times, and a predominance of traversing rather than pausing behaviors. These squares often experience lower internal safety levels, reflecting the dynamic nature of their environments.

3.2.2. Results and analysis of vitality construction (B2)

(1) Urban block dimension

Space syntax theory provides a quantitative analysis of spatial relationships based on spatial topological forms. In this context, "choice" quantifies how often a spatial element represents the shortest topological path between two points in a system, indicating its status as a favored route and its likelihood of traversal. Correspondingly, "integration" indicates the degree of connectivity of a spatial element with other elements in the system, measuring the centrality of that space within the overall system (Sheng et al., 2018). This highlights the ability of a space to attract pedestrian flows. Figures 5–7 present the analyses of integration (Spatial Permeability D4), choice (Spatial Centrality D5), and Urban Texture (D6) for the

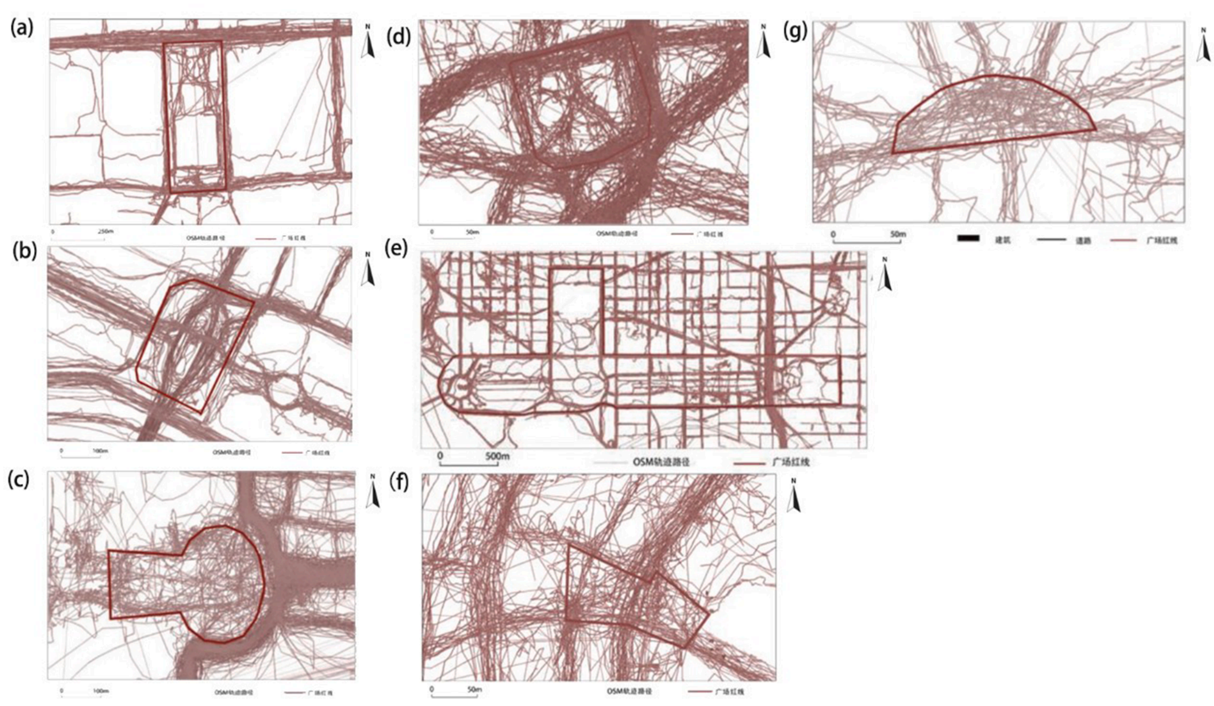

Fig. 4 Behavioral trajectory diagram. (a) Tiananmen Square; (b) National Mall; (c) Puerta del Sol; (d) Dam Square; (e) Place de la Concorde; (f) Trafalgar Square; (g) Piazza San Pietro.

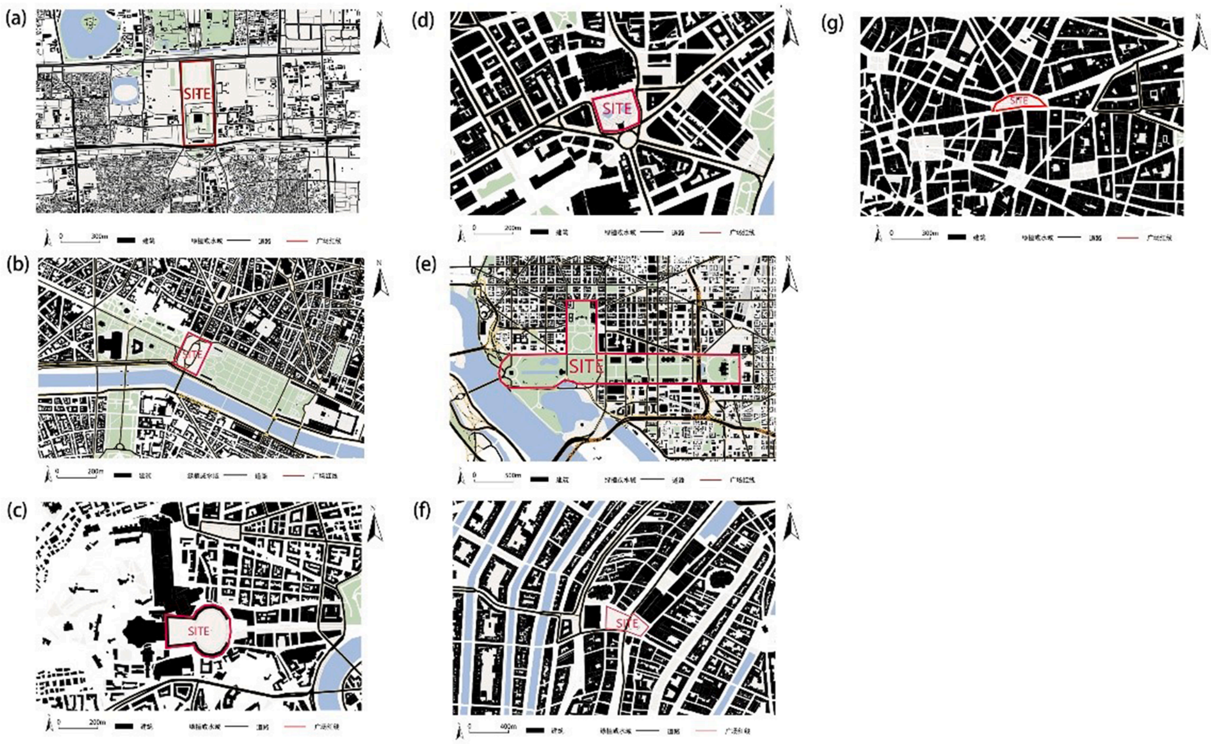

Fig. 5 Urban texture. (a) Tiananmen Square; (b) National Mall; (c) Puerta del Sol; (d) Dam Square; (e) Place de la Concorde; (f) Trafalgar Square; (g) Piazza San Pietro.

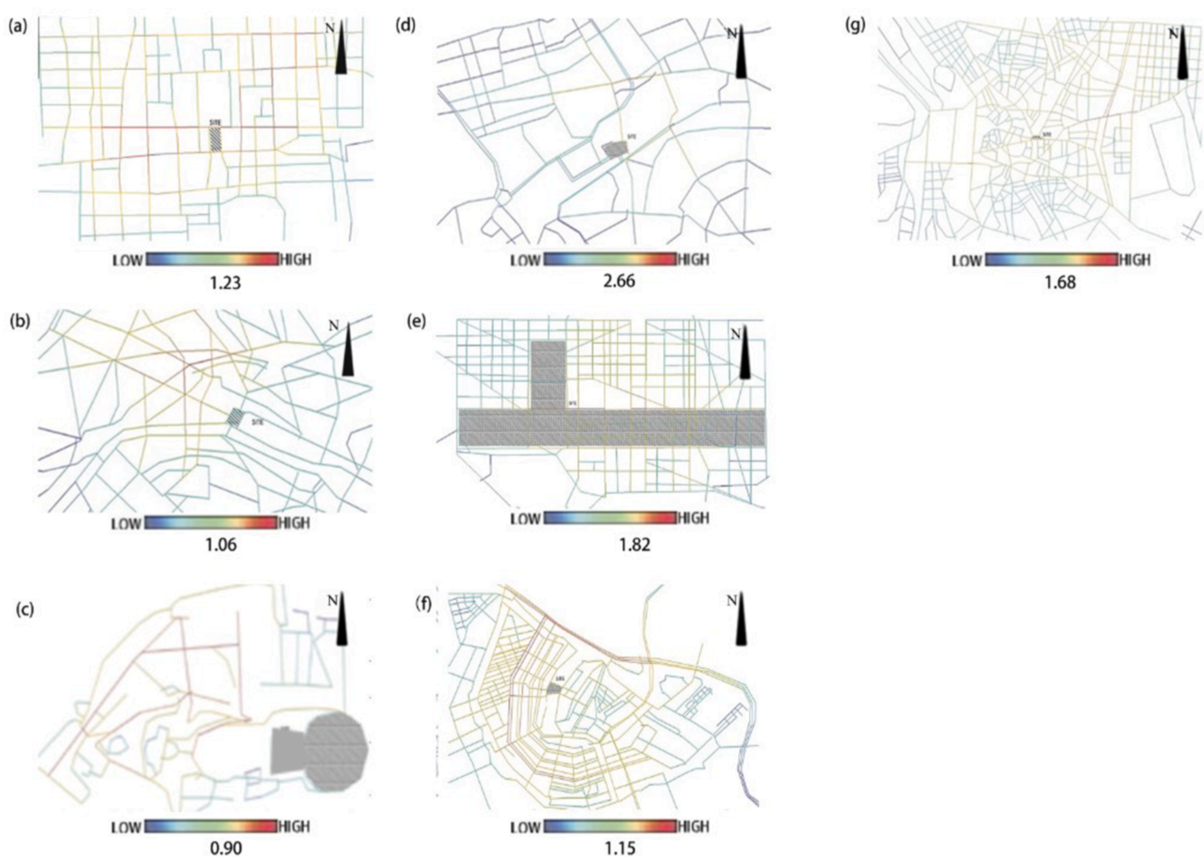

Fig. 6 Choice segment map. (a) Tiananmen Square; (b) National Mall; (c) Dam Square; (d) Puerta del Sol; (e) Place de la Concorde; (f) Trafalgar Square; (g) Piazza San Pietro.

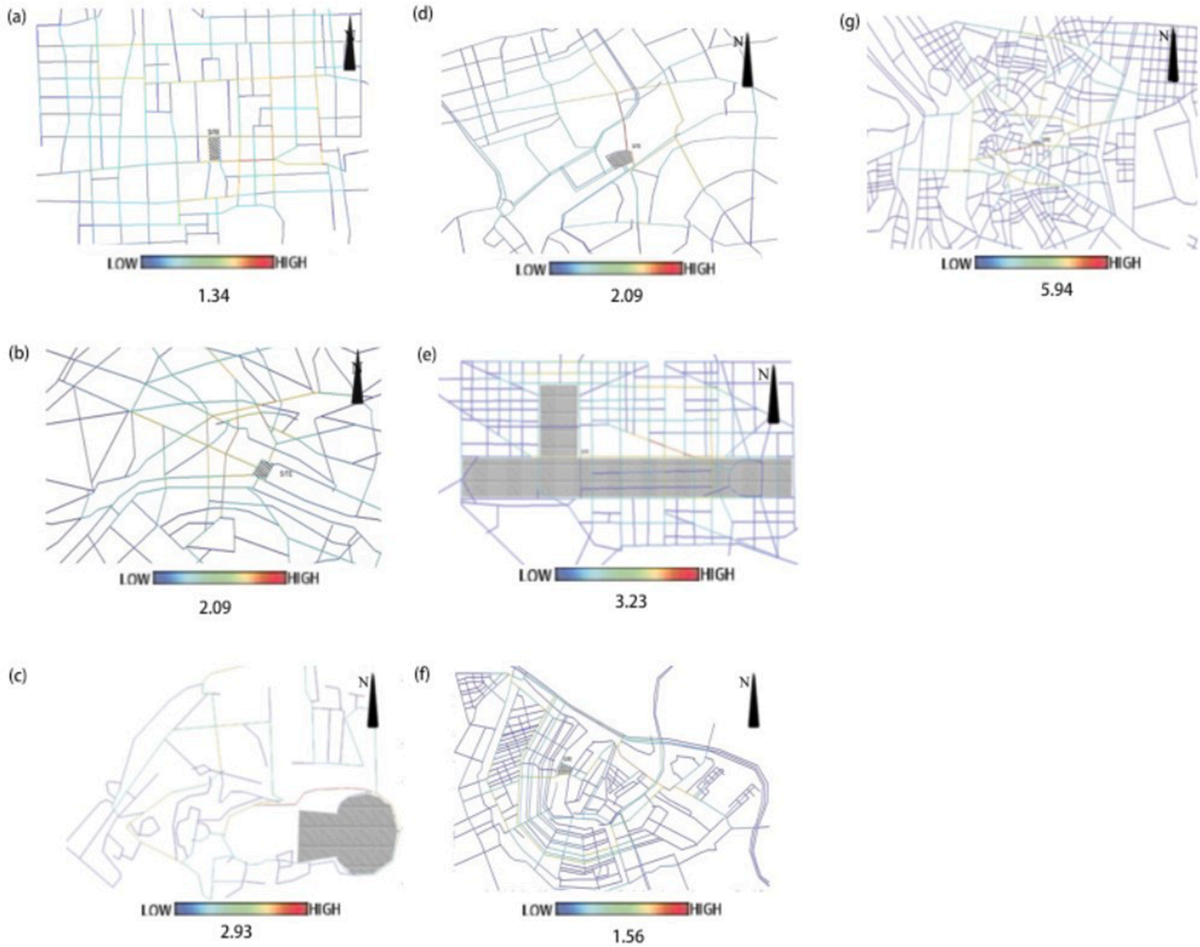

Fig. 7 Integration segment map. (a) Tiananmen Square; (b) National Mall; (c) Dam Square; (d) Puerta del Sol; (e) Place de la Concorde; (f) Trafalgar Square; (g) Piazza San Pietro.

seven national squares.[3] Figures 6 and 7 were created using DepthmapX software.

The analysis of Spatial Permeability (D4) and Spatial Centrality (D5) data shows that all seven squares exhibit high integration, indicating strong spatial centripetal forces that effectively draw pedestrian flows. High integration spaces typically encourage behaviors such as pausing and interaction. Notably, both Puerta del Sol and the National Mall show significant choice and integration, enhancing Spatial Permeability (D4), accessibility, and overall usability. For example, the National Mall's expansive layout, organized into a grid system, facilitates high accessibility across multiple blocks. In contrast, Puerta del Sol's radial road layout enhances the vitality of its internal space.

The Urban Texture (D6) analysis indicates that national squares are typically located in strategic core areas of cities, influenced by urban planning, leading to distinct internal spatial characteristics. The urban textures of cities like Spain and London are characterized by smaller blocks, leading to Puerta del Sol and Trafalgar Square becoming visual focal points within narrow street corridors. Another typical texture is the grid layout: The National Mall's grid plan uses diagonal streets to connect the National Mall to other iconic urban spaces, while Tiananmen Square's placement along Beijing's central axis enhances the symmetry of the city's main thoroughfare.

(2) Square dimension

[3] Data normalization is a method that adjusts individual features to a uniform scale, enabling standardized comparisons across different measurements. In our research, we apply normalized integration and choice metrics to assess the vibrancy of seven national squares, with data gathered from an area of roughly 50 square kilometers for each square. This approach helps to minimize the impact of urban environmental variables on our findings. Notably, for Vatican City, due to its smaller size, we focused our analysis on the national road network.
We calculate normalized integration and choice using the following formulas:

$$\boldsymbol{Integration} = \sum_{i=1}^{n}(\boldsymbol{road}_{\boldsymbol{lengthi}} \times \boldsymbol{Integration}_i)/(\boldsymbol{L} \times \boldsymbol{I})$$

$$\boldsymbol{Choice} = \sum_{i=1}^{n}(\boldsymbol{road}_{\boldsymbol{lengthi}} \times \boldsymbol{Choice}_i)/(\boldsymbol{L} \times \boldsymbol{C})$$

In these formulas, Integration measures a square's accessibility, where n is the number of surrounding roads, $road\_length_i$ is the length of each road, and $Integration_i$ is the respective road's integration value. I represents the average integration across the study area. Similarly, Choice indicates the likelihood of a square being used as a traversal route, with $Choice_i$ reflecting the choice value of each road. These normalization techniques ensure that our vibrancy comparisons across various regions are consistent and equitable.

Table 8 Vitality construction data results—square dimension.

Functional attribute classification	National square name & country	Spatial comfort		Spatial safety	Spatial aesthetics	Spatial function	
		Square scale (km^2)	Green coverage			Internal spatial activities	Surrounding building attributes
National memorial square	Tiananmen Square, China	4	0.5%	Segregated pedestrian and vehicle flows	Chairman Mao memorial Hall, monument to the People's heroes, tiananmen tower	Parades, celebrations, gatherings, commemorations	National museum, government buildings, city park, historical landmarks
	The National Mall, USA	24.3	90%	No Segregation of pedestrian and vehicle flows	Washington monument, lincoln memorial, WWII and Vietnam memorials	National ceremonies, protests	Government buildings, shopping malls
Political and commercial center square	Dam Square, Netherlands	0.14	0.5%	No Segregation of pedestrian and vehicle flows	Monument, royal palace of Amsterdam	Political and commercial center, street performances	New church, shops, madame tussauds
	Puerta del Sol, Spain	0.12	2%	Segregated pedestrian and vehicle flows	Fountain, bear and strawberry tree statue	Political and commercial center, Children's play area	Shopping malls
Transportation hub	Place de la Concorde, France	0.84	5%	Heavy traffic	Egyptian obelisk, ferris wheel, fountains	Political and commercial center	Museums, embassies, naval headquarters, gardens
	Trafalgar Square, UK	0.095	2%	Heavy traffic	Nelson's column, national gallery, national portrait gallery	Christmas celebrations, political protests, transportation hub	Papal residence, churches, parks, cemetery
Religious and monumental square	Piazza San Pietro, Vatican city	0.35	0.5%	Segregated pedestrian and vehicle flows	St. Peter's basilica, obelisk	Large-scale religious events by the Vatican	Papal residence, churches, parks, cemetery

This section examines the vitality construction at the square dimension. National squares serve not only as spatial entities but also as significant venues for cultural and social activities. Table 8 categorizes the squares into four functional types: political and commercial centers, transportation hubs, religious sites, and historical sites, to facilitate a structured discussion. By conducting an in-depth analysis of seven representative national squares, this study explores their spatial characteristics, functional roles, internal amenities, and surrounding environments. This approach reveals the unique features of these squares across spatial, functional, and environmental dimensions.

In analyzing the Spatial Comfort (D7) of national squares, this study identifies spatial scale and shading as critical factors. The scoring results revealed that smaller-scale squares tend to receive higher scores, as they provide more intimate and comfortable environments, encouraging people to linger and rest. Figure 7 compares street view images of national squares with different functional attributes. The three-level perspective view shows that political and commercial squares have less visible sky and tend to offer more suitable spaces for social interactions (see Fig. 7) (Kent and Schiavon, 2020). Urban climate also plays a significant role; in areas with strong sunlight or high winds, effective shading is crucial, while pleasant climates should prioritize amenities that encourage pausing. Monumental national squares, characterized by larger spatial scales and flexible layouts, often incorporate greenery to enhance comfort. For instance, the National Mall offers a welcoming environment with its extensive greenery, which encourages people to stay and relax (Kent and Schiavon, 2020). Conversely, squares located in political and commercial centers, as well as transportation hubs, often align with urban block scales but have significantly reduced green spaces.

In examining spatial safety (D8), national memorial squares generally exhibit a strong sense of safety and ambiance, leading to higher expert ratings. Transportation hub squares like Place de la Concorde and Trafalgar Square show no notable differences in safety scores despite their complex traffic systems. These squares utilize granite paving to reduce vehicle speeds, thereby enhancing safety to some extent. However, Trafalgar Square's 1988 renovation, which converted part of the roadway into pedestrian space, notably increased foot traffic and improved spatial vitality.

Regarding Spatial Aesthetics (D9), national squares demonstrate exemplary design, earning high ratings from experts and effectively promoting behaviors such as pausing and boundary crossing. The layout of Tiananmen Square exemplifies the symmetry and solemnity of traditional imperial architecture, while the National Mall features a

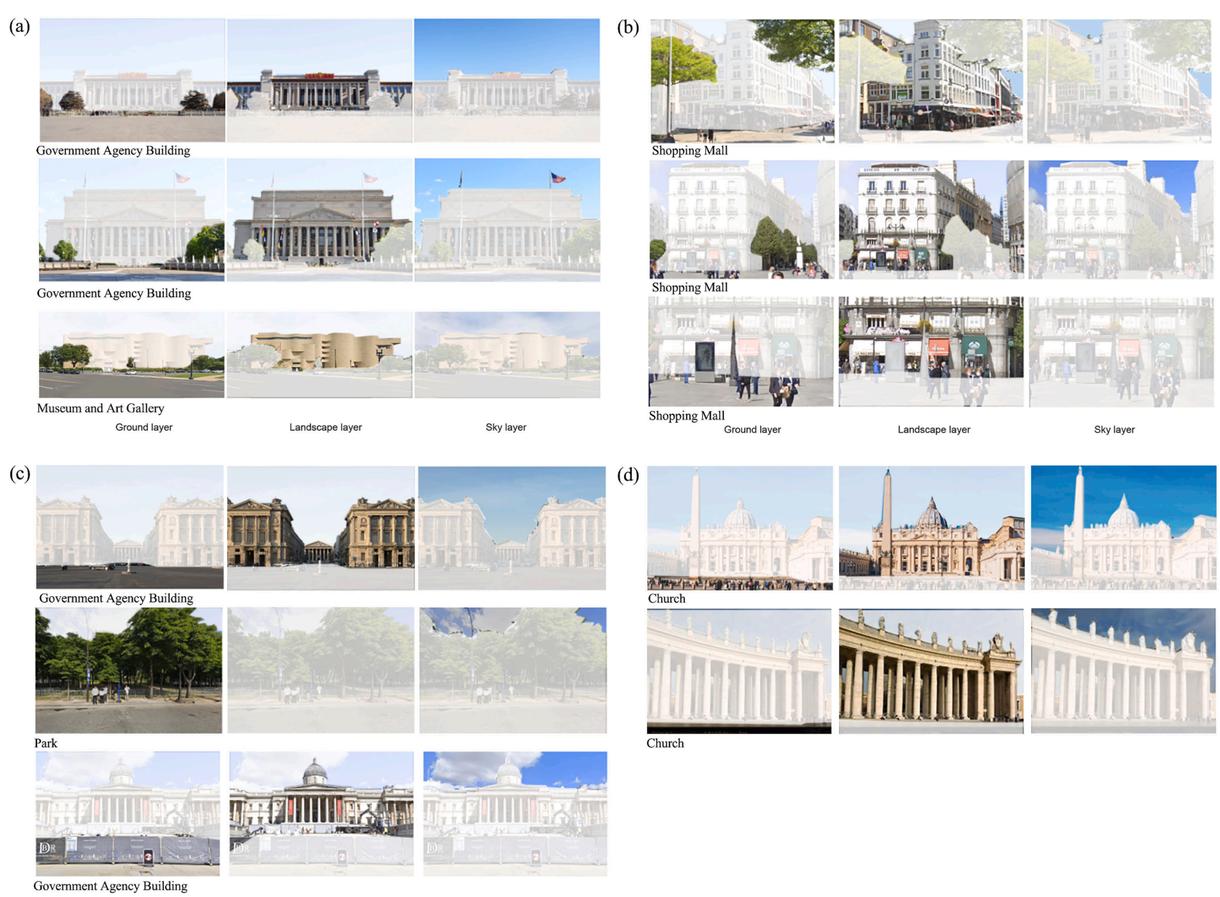

Fig. 8 Functional buildings and environment surrounding the square. (a) National memorial square; (b) political and commercial center square; (c) transportation hub square; (d) religious and heritage square.

Table 9 Relationships between vitality representation (B1) and vitality construction (B2).

Vitality representation (B1)	Related vitality construction elements
Pausing	Spatial centrality (D5): High integration level Spatial comfort (D7): High greening ratio and suitable scale Spatial safety (D8): Separation of pedestrians and vehicles Spatial aesthetics (D9): Visibility of architectural features Spatial Functionality (D10): Resting and shading facilities
Interacting	Spatial centrality (D5): High integration level Spatial permeability (D4): High level of choice in movement Spatial comfort (D7): High greening and appropriate scale Spatial safety (D8): Separation of pedestrians and vehicles Spatial functionality (D10): Rich activities and building attributes
Traversing	Spatial permeability (D4): High spatial choice
Boundary crossing	Spatial aesthetics (D9): Design promoting spatial permeability Spatial comfort (D7): High greening ratio and appropriate scale

stately grid complemented by diagonal sightlines. The architecture in political and commercial squares, along with transportation hubs, reflects national aesthetics, fostering a sense of cohesion and identity. The colonnades around Piazza San Pietro enhance its enclosure and encourage Boundary crossing, enriching the spatial experience.

When considering Spatial Functionality (D10), scores for national squares are generally high (see Fig. 8). National memorial squares symbolize administrative, commemorative, and cultural values, often surrounded by government institutions and museums that reflect a country's prestige. In contrast, political and commercial center squares, as well as transportation hubs, exhibit diverse and flexible functions. These spaces often feature churches and commercial facilities, fostering a relaxed social atmosphere. This environment encourages activities like street performances and market stalls, with outdoor seating areas providing opportunities for rest and social interaction. While the two transportation hub squares feature obelisks symbolizing national heritage, their facilities are minimal and not designed for prolonged stays. Piazza San Pietro, due to its religious significance, centers around the Pope and the basilica, emphasizing its unique spiritual importance. The compact layout of Vatican City is structured around St. Peter's Basilica, flanked by the Papal residence, churches, and cemeteries.

4. Conclusions

This study presents an analytical framework that combines various data types, including OpenStreetMap (OSM) trajectory data, space syntax parameters, and remote sensing imagery, with expert evaluations based on the Analytic Hierarchy Process (AHP). This approach comprehensive demonstrates the vitality mechanisms of national squares, offering a scientific foundation for understanding how behavioral patterns relate to spatial design. Furthermore, it provides a practical method for future studies on urban vitality and the improvement of square design. The key findings of the paper include:

1) A notable relationship exists between Behavioral Patterns (C1) in Vitality Representation (B1) and elements in Vitality Construction (B2). We identify four primary Behavioral Patterns (C1) in national square spaces: pausing, interacting, traversing, and boundary crossing. Designed elements like proper shading and appealing spatial scales normally encourage interaction and pausing. For instance, the small, segmented green spaces of the National Mall foster a comfortable atmosphere that promotes casual social interactions. Additionally, architectural design influences user behavior significantly, as observed in the permeable colonnade spaces of Piazza San Pietro, which facilitate "boundary crossing" behaviors and connect the cathedral with the city. Table 9 summarizes the relationship between Vitality Representation (B1) and Vitality Construction (B2).

2) There is also a significant relationship between Pedestrian Trajectories (C2) and Vitality Construction (B2) elements, particularly regarding Urban Texture (D6) and Spatial Functionality (D10). Urban texture directly affects the relationship between the square and its urban context, thus influencing user behavior. For example, as shown in Fig. 4, the radial road network of Puerta del Sol not only facilitates traversing behaviors but also enhances visibility. Moreover, Spatial Functionality (D10) actively shapes how spaces are used. Squares near religious or historical landmarks often promote free-flowing visitor paths, while transportation hubs typically accommodate more linear traffic flows.

National squares with different functional orientations have various demands for spatial Vitality Representation (B1). Commemorative squares, for instance, prioritize a solemn atmosphere that encourages behaviors such as "pausing" and "interacting." In contrast, squares functioning as political or commercial centers emphasize convenience and human-centered design, promoting behaviors like "interacting," "traversing," and "boundary crossing." While each type of square faces unique challenges, thoughtful spatial design and careful material selection can always minimize potential disruptions (Ren and Wang, 2018; Tie, 2017). Thus, the construction of vitality elements should be customized to meet specific needs, enhancing user comfort and connection while embodying national dignity.

This paper acknowledges limitations in scope and data, which prevents from a comprehensive exploration of certain vitality-related metrics, such as pedestrian flow analysis and comparative studies of spatial forms in national squares. Future research should seek to expand both the scope and depth of data, further investigating the intrinsic relationship between spatial forms and vitality in national squares. In this sense, this approach should be able to provide more thorough references and innovative insights for urban planning and square design.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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