Heliyon 10 (2024) e36761

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Correlation of unobserved factors of old town street walkability using SEM: Case study of old southern area, Nanjing

Xiao Han, Zhe Li *, Yinyin Cao, Zheng Zhou, Hengyi Zhao

Department of Landscape Architecture, School of Architecture, Southeast University, Nanjing, 210096, China

ARTICLE INFO

Keywords:
Old town street
Walkability
Unobserved factors
Correlation
Structural equation model (SEM)
Old southern area in Nanjing

ABSTRACT

Contemporary research on the walking environment focuses closely on the construction logic and internal correlation. Walkability is one of the vital characteristics of the old town street space. To understand how to improve the old town street space effectively, the investigation of the correlation mechanism of street walkability is essential. This study utilizes structural equation model (SEM) to construct a street walkability measurement model composed of four unobserved factors. Then, take Old Southern Area in Nanjing as an example, integrate Depthmap, ArcGIS and Python to obtain multi-source data, and establish a database of observed factors on street space. Finally, the matrix of the observed factors is set by SEM to calculate the correlation of the unobserved factors. This paper provides a novel technical approach for the correlation study of spatial construction logic as well as a reference for strengthening the spatial quality of the contemporary built environment.

1. Introduction

The contemporary built environment places a premium on the spatial construction logic, and related research has gradually developed from qualitative description to quantitative identification, from physical identification of observed factors to algorithmic analysis of unobserved factors. Unobserved factors, as a feature that cannot be directly measured, have led to growing emphasis on the spatial research of the built environment, which tends to be composite and multivariate [1]. Based on scientific cognition and quantitative measurement of unobserved factors of the built environment, a comprehensive exploration of its correlation mechanism is of great significance. Spatial analytic technique simulates spatial phenomena through statistical models, thus providing technical support for quantitatively analysing the correlation rules of such unobserved factors [2].

Walkability is a significant indicator of the urban pedestrian environment assessment [3]. Contemporary urban streets are no longer the traditional carrier dominated by traffic, but also an important activity space for providing social interaction. Contemporary urban residents' requirements for a high-quality walking environment cannot be met by maximising traffic efficiency [4,5]. Scientific research on the construction logic of street walkability and its influencing factors will help provide an objective basis for the scientific planning and renovation of the street environment as well as a research basis for shaping a high-quality walking environment.

The Old Town, a reasonably stable area established throughout urbanisation, serves as a crucial vehicle for the preservation of the traditional city's spatial form and the demonstration of its space performance. However, in the process of urban development around the world, the street spaces of old town areas have long been neglected and underestimated. This has gradually led to issues such as

* Corresponding author. Sipailou No.2, Xuanwu District, Southeast University, Nanjing, Jiangsu, China.
E-mail address: lizheseu@seu.edu.cn (Z. Li).

https://doi.org/10.1016/j.heliyon.2024.e36761
Received 22 March 2024; Received in revised form 3 August 2024; Accepted 21 August 2024
Available online 22 August 2024

insufficient functionality, loss of public attributes, imbalanced development of public spaces, and increasingly poor environmental conditions. As a result, people's willingness to visit has decreased while the vitality of such spaces has been lacking. Furthermore, most old towns find it challenging to fundamentally adapt their road patterns for historical reasons. China's urban construction and development enters a new phase focused on upgrading the existing built environment and conducting finer-grained management [6], enhancing the environments of historic city districts has currently become a topic of wide social concern. As a significant step towards bettering the street environment in the old town, the concept of urban micro-renewal emerges at a pivotal time in the face of numerous challenges [7]. By conducting detailed identification on the old town's street space, we can not only forestall the need for massive destruction and reconstruction, but also provide the groundwork for its restoration.

Contemporary studies on street walkability provide a more sophisticated and scientific study trend, propelled by multi-source data integration technologies [8]. The current study rests on two pillars: the acquisition of precise data on the street environment and the realisation of the quantitative expression of environmental variables. Key factors include an examination of the reasoning behind the construction of a quantitative analytical model of street walkability. Taking the old southern area in Nanjing as a research case, we construct a street walkability measurement system from four unobserved dimensions of feasibility, comfort, centrality, and convenience. Then, we integrate multi-source data such as road network data, point-of-interest (POI) data, and street view images (SVI) to quantitatively measure the influencing factors of street walkability. Consequently, we construct an analytical model of street walkability based on the structural equation model (SEM). Furthermore, the relationship of multi-dimensional data is quantitatively described via factor analysis, which provides the research basis and technical support for improving the precision of street space analysis and promoting the scientificity of urban renewal design and management.

2. Relevant research progress

2.1. Research on street walkability determinants

Different eras endow streets with different spatial characteristics and travelling capabilities, from the pedestrian streets that pursued aesthetics and order in the Renaissance, to the vehicle roads that pursued function and efficiency in the era of motor vehicles, to the period of returning to human nature when the shared street with quality and vitality was advocated, walking was given the highest priority again, and the street traffic suitability and environmental comfort also received attention. 'Walkability' refers to the degree to which the built environment accommodates walking, including providing a comfortable environment for pedestrians, enabling people to reach multiple destinations within a reasonable time and cost, and providing visual attraction on the journey in the walking network [9]. This concept was proposed in the late 1990s, and scholars and government agencies from various countries investigated the current situation at different levels related to walking in their own countries.

The research on the observed factors affecting pedestrian space has developed to a relatively mature stage. Relevant research has transitioned from observed to unobserved factors, and from quantitative identification to algorithm measurement and spatial information statistics integration [10–13]. Scholars and government institutions from various countries have developed relevant walkability measurement index systems based on the current spatial conditions of street spaces in their own urban cities [14]. With the deepening of research, researchers have established that many factors in the walking environment are theoretically abstract; that is, unobserved factors that cannot be directly measured or observed, and the measurement of observed factors is needed to realise the representation of unobserved factors [15], such as feasibility [16,17], comfort [18,19], convenience [20,21], centrality [22–24], and so on.

A shift from qualitative analysis to quantitative metrics has occurred in the corresponding field of study: the evaluation of perception preference based on questionnaires and interviews [25], the statistics of street micro-features based on audit tools [26,27], walking score evaluation based on network evaluation tools [28], and quantitative measurement of spatial information based on multi-source data [29,30]. While audit-based evaluations of street walkability have advanced to a useful stage, achieving large-scale data gathering and spatial refinement measurement at the municipal level remains a challenge. Moreover, owing to the respondents' diverse backgrounds, the collected data have certain limitations regarding validity and reliability. With the advancement of digital technology, the acquisition of spatial information has become more convenient in recent years, and the data types exhibit the characteristics of multi-source heterogeneity, such as POI, street network, street view image data [31–33], and so on, which respectively display the characteristics of street space from multiple angles and scales, and provide the possibility for accurate measurement of the street walkability.

Relevant studies demonstrate that contemporary urban streets have distinct walking behaviour characteristics and play a fundamental role in related research on pedestrian-friendly environments. The academic community has devoted considerable attention to the street walkability, which has resulted in a number of notable accomplishments. Current research is primarily focused on analysing the spatial morphological properties, integrating multi-source data to improve the accuracy of street space measurement, and on conducting correlation analysis to shed light on unobserved factors of street space.

2.2. Research on street walkability mechanisms

Based on previous explorations of streetscape environmental quality factors, empirical studies have increasingly examined the relationships between street space landscape metrics and walkability, highlighting the potential to improve walkability through modifications to the built environment. Overall, research has more comprehensively revealed the coupling mechanisms between spatial morphology and walkability, as well as the quantitative associations between different streetscape factors and walkability scores. Current studies commonly recognise that components of the street environment like traffic functionality, scenic qualities, and adjacent architecture can impact walkability. Researchers from diverse fields including architecture, urban planning, transportation, and behavioural psychology have also weighed in with multi-disciplinary perspectives. Their work has further analysed the underlying mechanisms by incorporating human behavioural and perceptual preferences [34,35].

From the perspective of research approaches, common methods include establishing walkability measurement systems and developing mathematical models to analyse the mechanisms of interaction between observed walkability indicators. Traditional linear causal relationship analysis models include regression and path analyses. Regression analysis is the basis for establishing linear causal relationship models and has been the most widely used mathematical model to date and can measure and validate the linear relationships between variables. For example, using multiple logistic regression models, Lin et al. compared the correlation strength between objective and subjective environmental attributes and physical activity [36]. Xu et al. adopted the macro functions and micro environmental elements of streets as independent variables, and pedestrian activities and subjective satisfaction as external dependent variables, analysed their underlying correlations through multiple linear regression models [37].

Path analysis further allows researchers to explore complex relationships between variables, including indirect effects and relationships between multiple dependent variables. These methods have been widely applied to test whether a variable (mediating variable) plays an intermediary role between the independent and dependent variables. For example, Dyck et al. examined the relationship between objectively assessed walkability characteristics and neighbourhood satisfaction and the mediating effects of physical environmental perceptions and moderate-to-vigorous physical activity on these associations [38]. Frehlich et al. focused on the mediating effects in the correlations between walkability, greenery, physical activity and health levels [39].

The fact that owing to the complex nature of street environment elements, and the differences in environmental conditions and developmental contexts between various study areas, the degree to which observed factors influence walkability also varies across different environments and developmental backgrounds is worth noting [40]. Additionally, unobserved factors may have complicated relationships with street physical characteristics [41], and existing research lacks in-depth data analysis of the causal relationship between unobserved factors that impact street walkability. Therefore, adopting statistical methods to integrate the observed and unobserved factors and measure their correlation mechanism followed by the formation of a practicable technical framework is an urgent task [42].

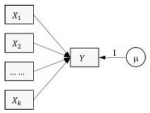
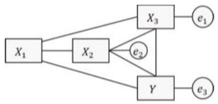
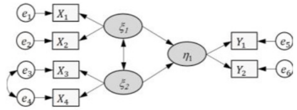
2.3. Application of structural equation model in street space research

In the previous section (2.2), traditional causal analysis models, such as regression analysis and path analysis, established a foundation for understanding the spatial characteristics of street space. However, these methods have limitations when dealing with complex relationships and latent variables. Structural Equation Model, as a statistical analysis method, effectively integrates factor analysis and path analysis to estimate causal relationships within theoretical models [43]. The core logic is to convert the causal relationship between variables to a matrix and calculate the matching degree between theoretical model and the measured data, so as to verify the reliability of the theoretical model. Aside from its obvious promise in ecological and behavioural sciences, economics, and others, SEM technology also has considerable implications for the field of urban design. SEM works well for constructing many types of assessment indicator systems, analysing the relationships between influential aspects, and data from multiple sources simultaneously. The model is a valuable tool for determining the relative importance of various environmental factors via numerical analysis.

Recent street space research has gradually shifted from social satisfaction and behavioural regulations based on the user's perspective to the assessment of street space quality [44–46]. The data sources for model fitting have expanded as a result of the development of digital technologies, going beyond simple sociological surveys and statistical data from questionnaires. The SEM has been expanded to include more influencing factors depending on environmental characteristics. Diverse parametric feature extraction strategies and the model analysis approach have contributed to the interdisciplinary of the research [47–49]. On the other hand, the SEM provides a scientific approach for walkability analysis in the space environment [50], enabling the quantitative measurement of spatial factor correlation mechanism supported by causal analysis models. For instance, Hahm et al. conducted a Global Positioning System (GPS) experiment observing pedestrians' choices of walking routes, and assessed their causal relationships with built environments using a SEM [51]. Similarly, Xing and Meng depicted urban landscapes by metrics such as the density of POIs, PLAND of buildings, LSI of buildings and density of roads, subsequently utilised SEM to determine the relations among urban landscapes and commercial patterns [52].

Table 1 summarises the characteristics of three common causal analysis models: regression analysis, path analysis, and structural equation model. It is evident that the methodology has evolved progressively from regression analysis to path analysis and then to structural equation model, with these three models being interconnected yet distinct. Compared to the first two traditional analytical techniques, SEM can solve the problem of variables that cannot be directly observed, and it has various advantages such as simultaneously testing the causal relationship between multi-dimensional observed and unobserved variables, and allowing both independent and dependent variables to contain measurement error [53]. Currently, numerical research on the built environment has been conducted, a preliminary research technique has been developed in conjunction with theoretical requirements, and the technological support system is progressively developing. The application of SEM technology to investigate the correlation between the spatial factors of old town street walkability needs to be further examined.

Table 1
Comparison of causal analysis models.

Causal model	Regression analysis	Path analysis	Structural equation model
Type of causal relationship	Unidirectional	Unidirectional, bidirectional	Unidirectional, bidirectional
Type of effect	Direct effect	Direct effect, Indirect effect	Direct effect, indirect effect
Type of variables	Measured variables	Measured variables	Measured variables, latent variables
Model diagram			
Modelling principles	Based on the methodology of linear causal relationship modelling, suitable for simple causal relationship studies	An extension of linear causal relationship modelling, suitable for causal relationship studies with mediating variables or bidirectional relationships	Focuses on exploring linear causal relationships involving latent variables, suitable for complex causal relationships with measurement errors and latent variables
Advantages	1. Mature theories and methods 2. Requires a smaller sample size	1. Can analyse reciprocal causal variables 2. Can measure indirect effects	1. Can handle multiple dependent variables simultaneously 2. Allows for measurement errors in both independent and dependent variables 3. Can estimate factor structure and factor relationships simultaneously 4. Provides greater flexibility in measurement models 5. Can estimate the overall model fit
Disadvantages	1. Authenticity of data fitting needs verification 2. Cannot handle situations with more than one dependent variable 3. Cannot handle unmeasurable variables 4. Does not allow for variable errors	1. Can only observe causal relationships among manifest variables 2. Does not allow for variable errors	1. Requires a large sample size 2. The model testing and modification process may compromise the initial theoretical model
Source of literature	Jin (2008) [54], Chatterjee and Simonoff (2013) [55]	Streiner (2005) [56]	Doloi, Iyer and Sawhney (2011) [57]

3. Materials and methods

3.1. Technical route

To accomplish accurate measurement of street space, this study integrates multi-source data such as road network, SVI, and POI data. The SEM method is utilised to excavate the correlation mechanism of street walkability. The specific research steps were as follows (Fig. 1).

(1) Construction of street walkability measurement system. Based on the construction situation of the old town street, combined with the existing research and data availability, the observed indicators of street space were selected, and the measurement system of street walkability constructed.
(2) Data collection of observed factors. Python and Depthmap software were used to collect raw data of the old southern area in Nanjing, which was loaded into the ArcGIS platform to develop an observed factor database for subsequent parameter estimation into SEM.
(3) Parameter of SEM. The data of observed factors were imported into AMOS software for SEM analysis, and the correlation measurement model of unobserved factors of old town street walkability was formed by parameter estimation and fitting indicator test.
(4) Correlation analysis of street walkability. Via the quantitative interpretation of the fractal properties of the observed factors and the correlation degree of the unobserved factors, the correlation analysis of the latter of the old town street walkability is realised.

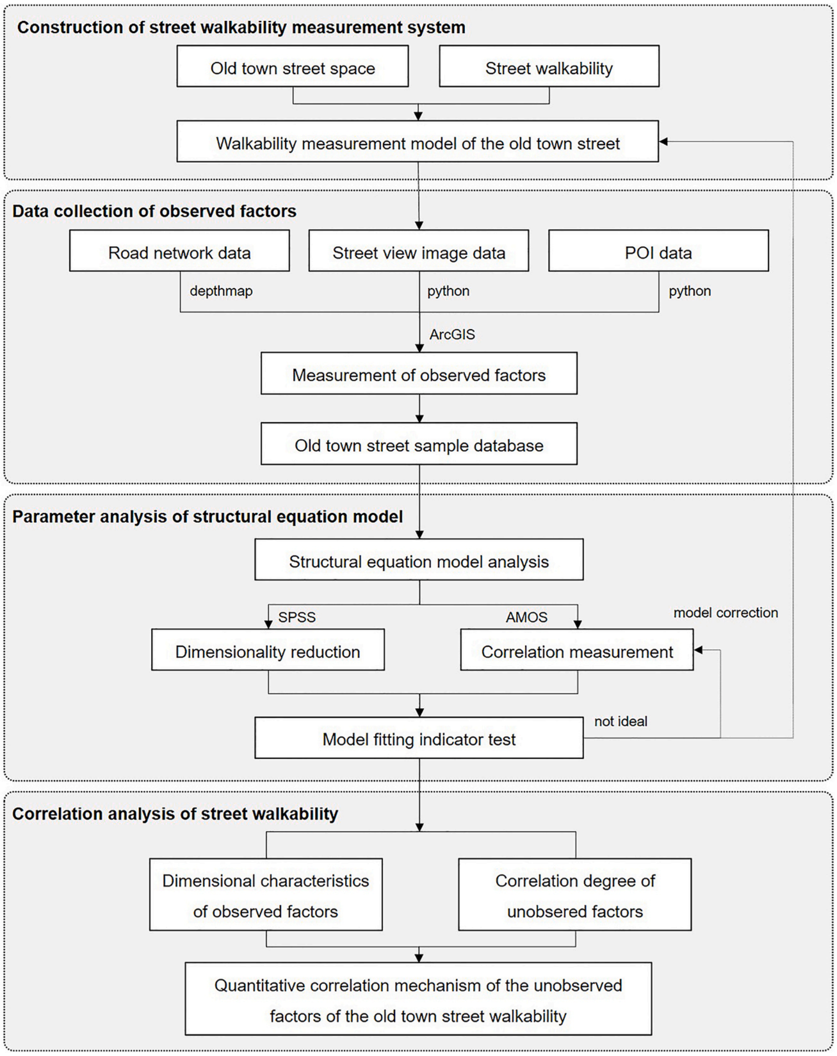


Fig. 1. Methodological framework for street walkability analysis.

3.2. Construction of street walkability measurement system

On the basis of summarising measurement systems proposed by relevant studies and considering the availability of data, the core influencing factors of street walkability are summarised into four unobserved and 15 observed factors (Table 2). Among them, feasibility entails that the road network is continuous, and can provide pedestrians with sufficient path selection possibilities. Convenience means that urban streets can provide pedestrians with sufficient services and fulfil their needs for various functions. Comfort refers to the urban street space that can provide pedestrians with a comfortable walking experience and pleasant visual perception. Centrality refers to the possibility of pedestrians gathering in a certain area.

3.3. Research object and scope definition

Taking old southern area in Nanjing as a case study, the street walkability measurement model is constructed along with the correlation of unobserved factors. The old southern area is located in Qinhuai District, Nanjing, east and west to Ming Dynasty City Wall, south to Zhonghua Gate, north to Baixia Road, with a total study area of 600 ha (Fig. 2). Since the mid-Ming Dynasty (1360s), the old southern area has been the most densely populated area of commerce and residence, and its urban streets have also undergone a process from a walking to vehicle traffic environment, and then returning to a human-oriented walking environment. With the fast expansion of urbanisation and the modernisation of the main urban area, numerous problems exist in the old town street space, such as the encroachment of vehicles into pedestrian lanes, and the low quality of street landscape. Therefore, the old southern area in Nanjing is not only a case of the progression research of walkability, but also a representative sample for the study of urban street walkability from a humanistic scale. This study defines the research scope as the space between the road red line and the building boundary, including the topological road network and the three-dimensional street space.

3.4. Data collection

According to the street walkability measurement system constructed above, the data of all observed factors need to be recorded into the geographic database for format conversion and spatial analysis. The data type include road network data in CAD format, SVI, and POI data.

Among them, the CAD drawing data originates from the government digital map of Qinhuai District, Nanjing, China in 2017, which is applied primarily for geographic coordinate positioning and providing physical space data. The road network data were topologically processed, and simplified to the road centre line, yielding 199 valid road network data observations (Fig. 3). Then, we imported the road network data into Depthmap software, and measured the degree of connectivity, integration, topology depth, and betweenness. In addition, the road boundary and road centreline are organised so that they can be imported into the ArcGIS platform to measure the physical observed factors of the street.

Then, by writing a Python programme, taking the midpoint and endpoint of the road as sampling points, the street view image data and POI data were gathered by inputting the sight angle and viewpoint position (Fig. 4). After completing the digital capture, using the neural network model and machine deep learning data sets, we extract main elements such as greenery, sky, pedestrian lanes, vehicle lanes, and building facades in the SVI, and then calculate the pixel area ratio of each element (Fig. 5). The 3393 collected POI data observations were further divided into 12 types of fundamental functions, including catering, shopping, community services, medical care, parks, accommodation, sports, housing, government agencies, education, banks, companies, and enterprises. Then, we used the ArcGIS platform to ascertain the sorts of POIs covered by each street with a buffer of 50 m. This distance also corresponds to the scale at which individuals can observe the sides of the road while casually strolling through urban street spaces [37].

Table 2
Street walkability measurement indicator system.

Unobserved factors	Observed factors	Quantitative description
Comfort	Street width	The distance between buildings on both sides of the street
	Building height	Average height of buildings facing the street
	Distance-to-height ratio (D/H)	The ratio of the building height to the street length
	Pedestrian rate	The ratio of the area occupied by pedestrian lanes to the area occupied by vehicle lanes in the street view image
	Sky view ratio	The ratio of the area of the sky to the total street view image
Feasibility	Street length	Length of the road centreline
	Connectivity	The number of connections from a street to other adjacent streets
	Betweenness	The number of spatial conversions from a street to all other streets
Centrality	Integration	The number of direction changes from a street to all other streets
	Topology depth	The topological distances from a street to all other streets
	Green view ratio	The ratio of the area of greenery to the total area of street view image
Convenience	POI diversity	Types of POIs covered within 50 m of the street
	POI density	The ratio of the number of POIs covered within 50 m of the street to the length of the street
	Intersection density	The number of all intersections in this street
	Public transport density	The number of public transport stops covered within 50 m of the street

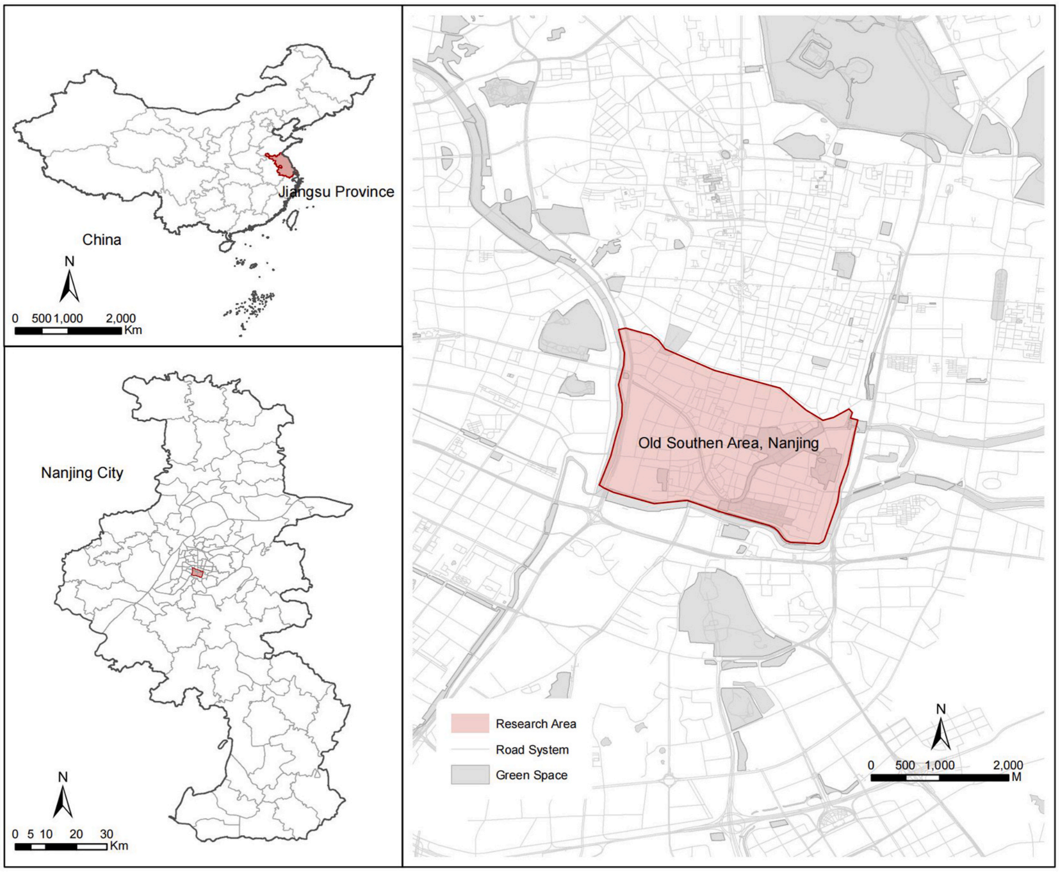


Fig. 2. Location of the old southern area in Nanjing.

Following the data collection, the identification results with geographic coordinate information are projected into the urban space to analyse the composition of the walkability influencing factors of each street. Each factor data of each street is aggregated as average to form a table and normalised to develop correlation analysis of unobserved factors of street walkability.

4. Quantitative research results of old town street walkability

4.1. Exploratory factor analysis based on SPSS

After collecting 15 normalised factors, we performed exploratory factor analysis (EFA) in SPSS 26 to divide the observed factors into theoretically significant groupings, that is, unobserved factors. The results of EFA are reported in Table 3.

According to the Kaiser–Meyer–Olkin (KMO) and Bartlett's test results, the KMO sampling adequacy is more significant than 0.6, and the significance level of the Bartlett test is less than 0.001. The variables were initially screened according to the common factor variance, and four variables (street aspect ratio, relative walking width, POI density, and public transport density) with an extracted value less than 0.5 were eliminated and finally 11 variables were retrieved.

Principal component analysis was used to extract the unobserved factors, and the maximum variance rotation method was used to extract the common factors. A total of four principal components were extracted, including four important factors: feasibility, comfort, centrality, and convenience. The cumulative variance percentage explained by the above four categories of common factors to the dataset is 70.271 %, which is higher than the critical value of 60 %. In addition, the absolute value of factor loading of each observed factor is greater than 0.5, indicating that the convergent and discriminant validity of each variable meet the requirements.

4.2. Confirmatory factor analysis based on SEM

We employed AMOS 24 software to develop the correlation path map, and imported the normalised data for confirmatory factor analysis to measure the relationship between the four unobserved factors and walkability.

The fitting results are presented in Table 4; the absolute fitting indicator χ^2/df is 1.177, the RMSEA is 0.029, and GFI is 0.965. The relative fitting indicator NFI and CFI of the model are 0.893 and 0.981, respectively. The parsimony fitting indicator PNFI and PGFI are

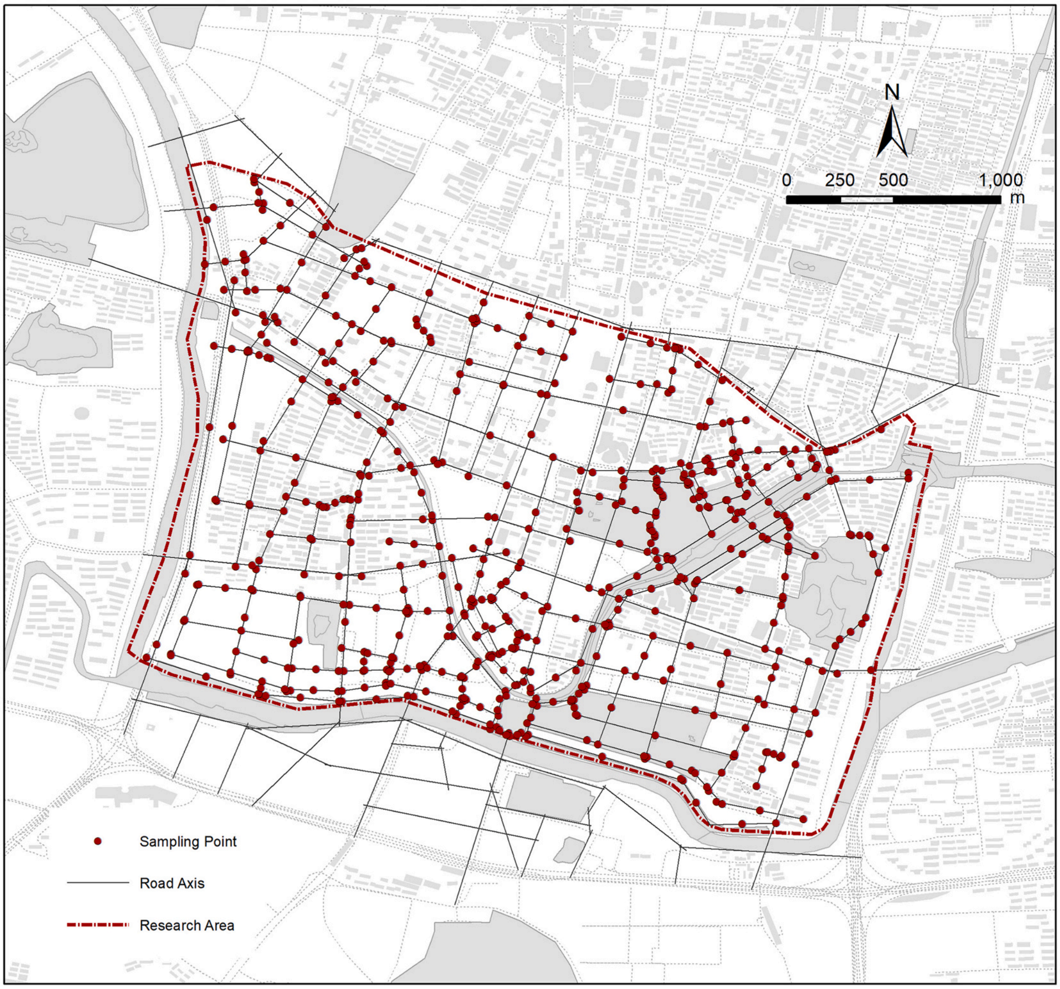


Fig. 3. Road network data and sampling point.

0.568 and 0.512, respectively. All of them fall in the ideal range, thus indicating that the assumed theoretical model had a high degree of fit with the observed data.

The path coefficient between each unobserved factor and the street walkability was fitted through the SEM. The greater the coefficient, the more important the factor is to the casual relationship. The estimated results (Table 5 and Fig. 6) indicate that the four unobserved factors all have a positive effect on the walkability. Centrality and feasibility are the most influential factors of walkability, whereas convenience has a relatively weak impact.

4.3. Spatial analysis of street walkability

Based on the correlation results measured by SEM, the standard path coefficient was taken as the weight value of each factor. Then, the non-dimensional factor drawings were superimposed with weight to obtain the spatial distribution of the four unobserved factors and the walkability measurement drawings (Fig. 7). We divided the values of each factor into nine levels at quantile breaks in classification. Colours from blue to red represent walkability from low to high, respectively.

Furthermore, we performed hotspot analysis of walkability in ArcGIS platform to generate spatial clustering with statistical significance. The Moran's Index of the walkability in the old southern area in Nanjing reveals that the values all pass the 1 % significance level test; the Moran's Index is 0.688, which indicates that the distribution of walkability has a high clustering phenomenon, that is, the high/low walkability value will positively/negatively affect the walkability value around it.

The spatial distribution of walkability exhibits a decreasing trend from the middle to the outside. Specifically, the red plaques represent the walkability in the high-value range, with 12.6 % of the areas having high walkability, which further influence the walkability of surrounding streets, being equally high. The area of red plaques is mainly concentrated on the main road in the middle of the study area. Yu Garden, East Zhonghua Gate Historical Block, Wuding Gate Park, Confucius Temple along the Qinhuai River, and so on, are involved, which have famous attractions, historical blocks, industrial park, and so on. In 10.7 % of the areas, the walkability is

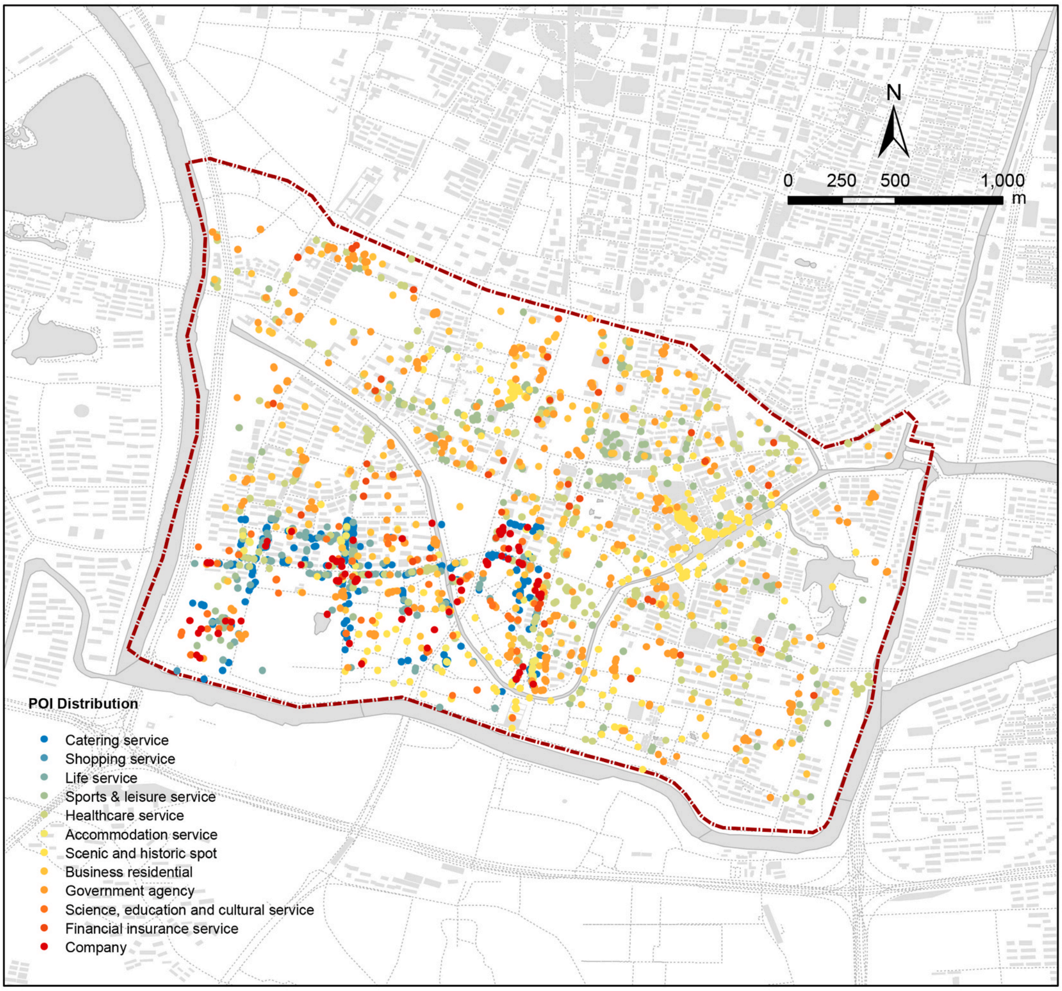


Fig. 4. POI data extraction results.

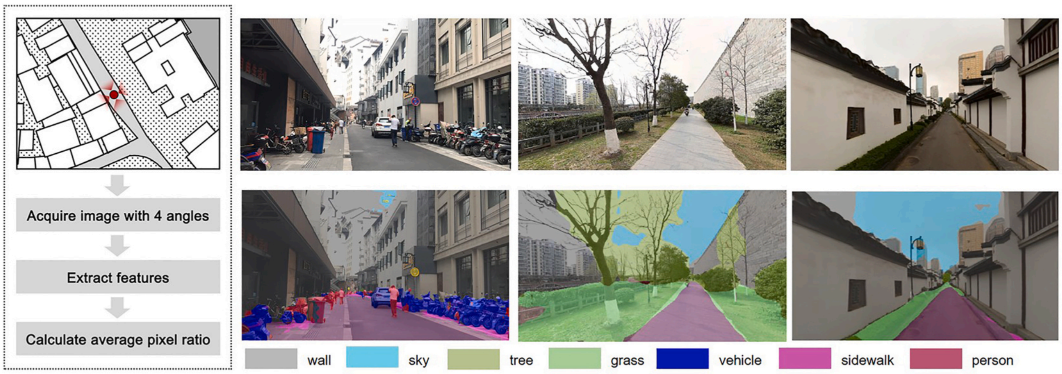


Fig. 5. Element identification results of street view images.

Table 3
Factor loading and commonality.

Unobserved factors	Observed factors	Communality	Factor loading	Variance explained (%)	Cumulative variance (%)
Feasibility	Betweenness	0.818	0.899	32.231	32.231
	Connectivity	0.854	0.898		
	Street length	0.765	0.856		
Comfort	Sky view ratio	0.631	0.764	13.435	45.666
	Building height	0.703	0.749		
	Street width	0.654	0.719		
Centrality	Topology depth	0.802	0.805	12.879	58.545
	Integration	0.864	−0.791		
	Green view ratio	0.418	−0.515		
Convenience	POI diversity	0.657	0.766	11.726	70.271
	Intersection density	0.564	0.713		

Table 4
Model fitting results.

Fitting indicator	Fitting standard	Fitting result	Results explanation
χ^2/df	$1<\chi^2/df < 3$	1.177	Ideal
RMSEA	>0.10	0.029	Ideal
GFI	>0.80	0.965	Ideal
NFI	>0.80	0.893	Relatively ideal
CFI	>0.80	0.981	Ideal
PNFI	>0.50	0.568	Ideal
PGFI	>0.50	0.512	Ideal

Table 5
Standardised path coefficient estimates of the structural equation model.

Path	Path direction	Estimate	
Street walkability	Feasibility	0.616	***
	Centrality	0.666	***
	Comfort	0.501	***
	Convenience	0.230	
Feasibility	Connectivity	0.963	***
	Betweenness	0.839	***
	Street length	0.818	***
Centrality	Topology depth	0.830	***
	Integration	−0.913	***
	Green view ratio	−0.054	
Comfort	Sky view ratio	0.693	***
	Road width	0.682	***
	Building height	0.440	***
Convenience	POI diversity	0.177	***
	Intersection density	0.622	

***$p < 0.001$.

in the low range. For example, blocks in the northeast and southeast corners of the study area have large blue plaques, which are dominated by old residential areas.

5. Discussion

The correlation analysis results emphasised the importance of various observed factors in influencing street walkability. For different dependent variables, the significant levels and effect sizes of various factors are not exactly the same. Accordingly, the demands and sensitivities to factors under different dimensions of walkability are different. Specifically, centrality and feasibility are the main dimensions influencing walkability. Among the factors that exert a positive influence, connectivity, topological depth, betweenness, street length displayed comprehensive and strong effects, and they all respectively belong to the two dimensions of centrality and feasibility. The observed factors under comfort and convenience alone exerted weaker influences. Integration has the greatest negative impact on walkability.

We used the ArcGIS platform to map the results of the observed factors, thereby enabling the examination of the spatial distribution characteristics of the street walkability, and we incorporate the results of the path coefficients to discuss the correlation mechanisms of the observed factors under various dimensions.

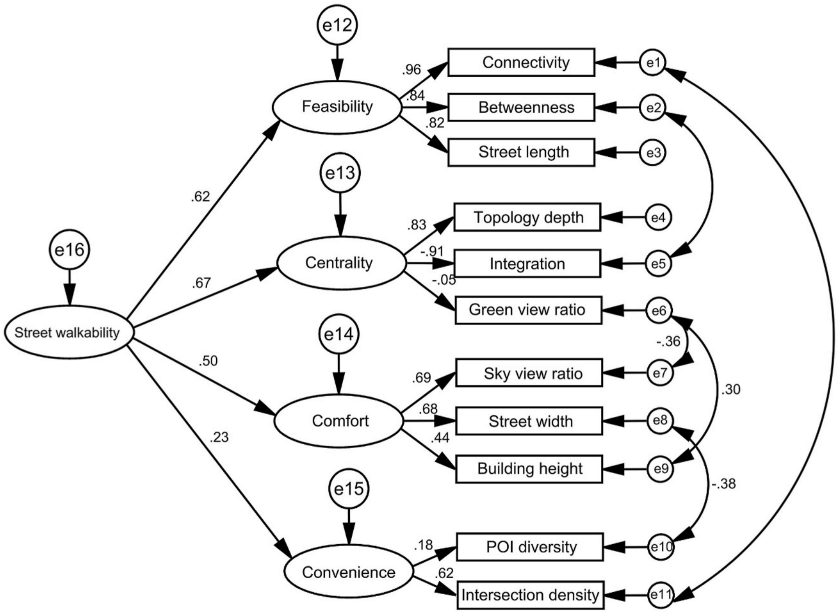


Fig. 6. Standardised path coefficient map.

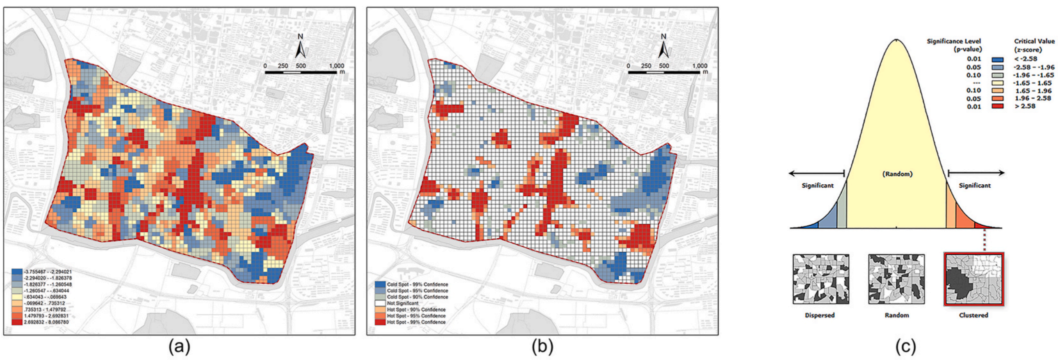


Fig. 7. The results of the walkabilty in Nanjing old southern area: (a) The result of the walkability; (b) Hotspot of the walkability; (c) The result of global spatial autocorrelation analysis.

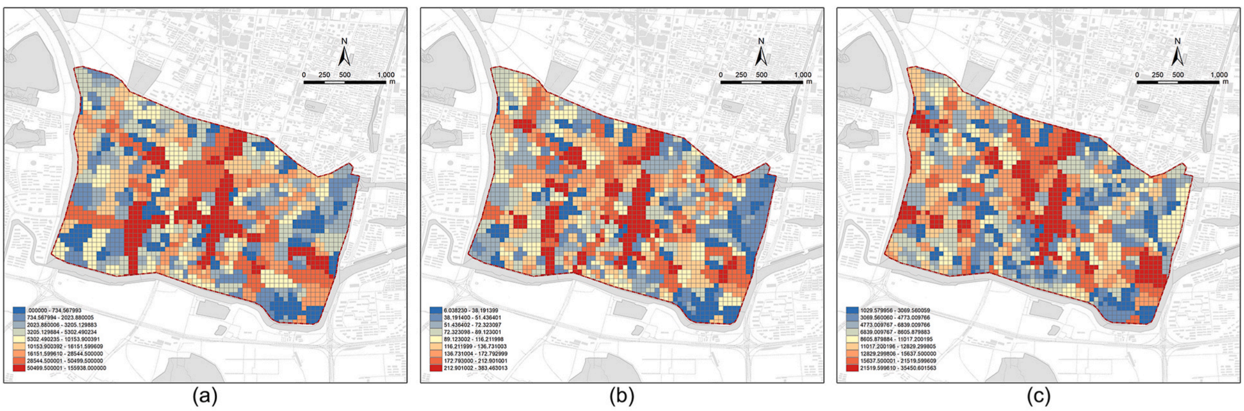


Fig. 8. The results of the observed factors of the feasibility: (a) betweenness; (b) connectivity; (c) street length.

5.1. Feasibility

The standardised path coefficient of feasibility is 0.62, and the three observed factors of connectivity, betweenness, and street length all display a substantial positive correlation with feasibility. The most fundamental function of streets is transportation. Convenient and efficient paths are the primary conditions for fulfilling the transportation function. Sugiyama et al. also confirmed that street connectivity was significantly associated with both recreational and utilitarian walking [58]. From the perspective of spatial distribution, the overall feasibility in the study area presents a distribution characteristic that the two roads in the inner centre, horizontal and vertical, which progressively diminishes to the outside (Fig. 8). Street betweenness and connectivity display similar characteristics. The high-value areas are also clustered near the main road in the middle of the study area, and the connectivity and betweenness near the Qinhuai River and Ming Dynasty City Wall on the south and east sides of the area are relatively low. It is more convenient for pedestrians to traverse the street space with the ideal route when the street interface is smooth and open, which increases the visual attraction and traffic connection between the street space and neighbouring streets. Streets with a high connectivity can link most of the area of the block and effectively gather popularity, which is consistent with Montgomery [59], that is, to increase the permeability of street space and provide more turning opportunities, thereby increasing potential passenger flow volume.

The scale distribution of the street blocks in the study area is not uniform, which is related to the evolution characteristics of the plot shape in the process of urban development. Traditional streets provide small-scale blocks because of their uneven surfaces and crannies, mainly distributed in residential areas in the middle of the west side and historical protection blocks in the south of the study area. Nonetheless, with the development of a graded street network and the presence of the large blocks, the size of the street increased notably in the crossing major road in the centre of the study area and the factory area in the southwest. According to the measurement, the street length is mostly distributed between 100 and 400 m and has a significant positive correlation with the connectivity and betweenness, thereby indicating that on the basis of adopting dense grid-shaped streets of small blocks, proper meeting of land development and function requirements will contribute to form good street feasibility and spatial characteristics. This is consistent with Doyle et al., who emphasise that scale, proportion of small blocks, and so on are important characteristics constituting a good walking environment [60].

5.2. Centrality

Centrality has the strongest positive correlation with street walkability (standardised path coefficient is 0.67). This finding confirms that the 'street network itself is the most influential factor in shaping mobility', as proposed by Turner [61]. Among them, topological depth has a positive influence on centrality, but integration is negatively correlated (standardized path coefficient is −0.91). From the computational principles of topological depth and integration, depth refers to the shortest topological distance from one axis to another within the system. Integration is the reciprocal of depth, which indicates the degree of aggregation and dispersion of the street and alley space [62]. The greater the integration, the higher the degree of aggregation of the space within the overall system, and it also indicates that the human flow within the space is relatively large.

The integration and depth value data can also reveal the hierarchy of streets and alleys. Within the street network, the main street in the area has the lowest spatial topology. This often extends from the main street to both sides to create branch roads, ultimately establishing clusters of stores and pedestrian crossings. The branches are situated at the perimeter of the street network, and in areas with a high topology depth. These streets are less accessible to pedestrians; hence they are more isolated, and the function is more single. To create a street space suitable for the dispersion of people flow and the growth of economic potential, investigation of the functions and connection of secondary roads is essential; otherwise, traffic congestion issues may arise [63]. Therefore, while guaranteeing the high integration of the main street, streets with clear topological characteristics can make its spatial organisation more intuitive for pedestrians.

The relationship between the green view ratio and centrality is relatively weak and negative (standardized path coefficient is

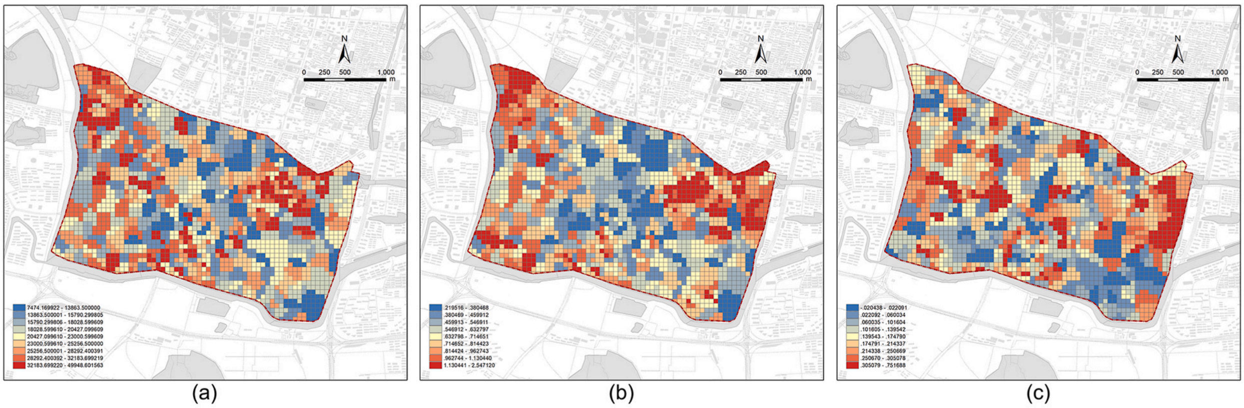


Fig. 9. The results of the observed factors of the centrality: (a) topology depth; (b) integration; (c) green view ratio.

−0.05), which is inconsistent with previous studies. While some research has demonstrated that street greenery can provide a range of health and well-being benefits [64–66] and also influence pedestrians' thermal comfort by encouraging them to walk in shaded areas [67], one exception is Jin's research [68], in which a negative correlation pattern was established between greenery level and walkability, which is consistent with our findings. This may be due to the fact that when people perceive the urban street environment dominated by buildings, greenery is perceived as the background elements, which are easy to ignore. In addition, excessive vegetation will inhibit the building interface, thus affecting the openness of the street space, and therefore affecting the orientation of pedestrians' vision and the choice of travel paths (Fig. 9).

5.3. Comfort

Factors related to comfort also have a significant impact on street walkability (standardized path coefficient is 0.50). Among them (Fig. 10), the coefficient of the sky view ratio is the highest (standardized path coefficient is 0.69), and that for building height is relatively low (standardized path coefficient is 0.44). This is consistent with Lin et al.'s findings; their study validated 'the importance of sky elements as indispensable and valuable elements in landscape perception' [69]. In terms of the spatial distribution of the factors, the sky view ratio presents the distribution characteristics of continuous internal holes, transparent, and open underlying the Ming Dynasty City Wall and Qinhuai River. In the Qinhuai River and historic district, the sky view ratio has a relatively high degree of influence on people's vision, and in combination with other environmental factors, it reflects people's perception orientation, whereas the main street in the centre of the area is in a relatively dim state.

The coupling analysis with the street level implies that the street comfort is related to the street level and the layout of the road system; the higher the road level, the wider the street. More than 60 % of the street width is distributed between 10 and 30 m. On the streets with a width of about 20–30 m, the vision on both sides can connect with each other, which is a visually pleasing, enclosed and intimate space for pedestrians [70]. Compared with these small-scaled streets, the street width of the main road surpasses the human scale, thereby making it difficult to create a sense of enclosure for pedestrians. The secondary division is typically accomplished by planting trees between the pedestrian path and the roadway to control the scale within an appropriate range.

The building height of the street interface also has a positive impact on walking experience and is strongly related to enclosure. On the one hand, different building heights can make people feel a sense of either broad and bright, or narrow and dark, that is, people's perception of the D/H in the street environment. On the other hand, the facade colour, shape, and style of the building have a stimulating influence on people's vision perception.

In addition, most of the street D/H ratios are between 1 and 2, which coincides with Ashuhara's theory presented in his book 'The Aesthetics of the Street' [71]. He summarised the street D/H ratios that make people feel intimate or distant, believing that a D/H ratio between 1:1 to 1:2 is a comfortable scale for street spaces. However, from the results of the correlation statistics, the D/H ratio is not related to the expected unobserved factors such as comfort and walkability. The primary reason is that the D/H ratio is a purely proportional numerical relationship, which ignores the different feelings of people with the same spatial scale but different distances; that is, the openness and enclosure of the space is not only affected by the ratio but also by the absolute size [72]. Consequently, a reasonable D/H ratio can only induce a strong perception of walkability within the appropriate scale of the street.

5.4. Convenience

The convenience of services has a positive correlation with street walkability, but the correlation is relatively weak in comparison to other factors (standardized path coefficient is 0.23). The influence of intersection density is the most noticeable (standardized path coefficient is 0.62), followed by POI diversity (standardized path coefficient is 0.18). We speculate that the instability of the influence of convenience may be because for recreational walking activities, pedestrians may not have a clear destination in the process of their stroll [73]; thus convenience is not the primary goal of consideration. Lu et al. also drew a similar conclusion [74].

The spatial distribution of intersections in the old southern area of Nanjing exhibits a strong positive correlation with the connectivity (Fig. 11). This finding corroborates Southworth's argument that street network plays an important role in street quality, and the reflected permeability will greatly affect the walkability [75]. Significant progress toward lessening traffic speeds and spreading out traffic flows can be made by intersections. Furthermore, presence of a varied range of businesses is another benefit of a street network with an appropriate density.

The POI density is substantially greater in the centre of the study area and is highest on both sides of the two main roads. The POI diversity indicates that the high-value spaces are mainly distributed in the historical blocks, such as the Confucius Temple, East Zhonghua Gate, which reveals that the single-street sections with high functional complexity have been formed, but the block network with complex and diverse functions has not yet been formed.

By contrast, the POI and public transport densities have no significant relationship with walkability. The reason may be due to the extensive differences in pedestrians' interests and daily requirements, thereby necessitating that streets be as complex as possible and have a wide variety of functions. The results of density only indicate the degree to which stores are concentrated along the street. Accordingly, it is only necessary to provide for the fundamental requirements and the accessibility of pedestrians on the basis of ensuring relatively intensive development, so as not to make the distance become the determining factor.

6. Conclusion and prospects

Taking the old southern area in Nanjing as an example, this study discussed the spatial characteristics and walkability. The SEM-

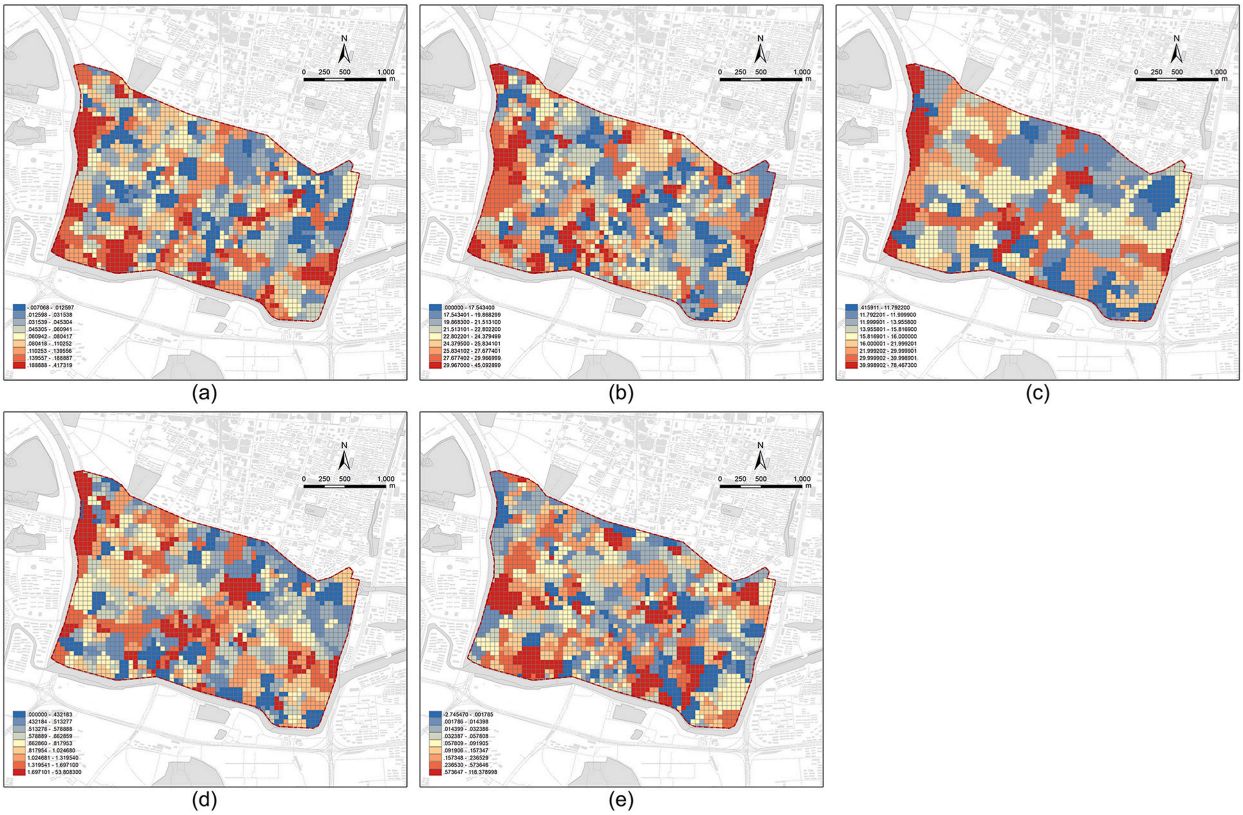


Fig. 10. The results of the observed factors of the comfort: (a) sky view ratio; (b) building height; (c) street width; (d) D/H; (e) pedestrian rate.

based measurement model of the street walkability was developed, and the degree of correlation between the four unobserved factors calculated. The model fit results suggest that the proposed walkability correlation measurement model demonstrates good calibration with empirical observations. Among the various factors, centrality and feasibility appear to be the primary determinants of walkability, while convenience exhibits a relatively weaker influence. Complex coupling relationships also exist between certain individual metrics, such as the integration and green view ratio exhibiting negative impacts on enclosure. When ensuring optimal values for key influential factors, equal attention must be paid to maintaining proper proportional relationships and combinatorial forms across all components.

The findings also provide clear guidance for practices and policymaking. From a spatial planning perspective, planners can integrate the results of correlation measurements to clarify the importance of physical conditions of old town streets to walkability and take factors with higher correlation as priority projects for updating, so as to improve the walkability of street spaces more effectively. Key strategies include optimising road layouts and ensuring high sky visibility to improve the comfort of walking environments, based on the correlation results related to connectivity, topological depth, choice, road length, and sky visibility. In addition, by analysing the actual measurement results and spatial distribution characteristics of each factor, planners can identify low-value aggregation spaces that need improvement, and propose corresponding environmental improvement strategies.

In terms of policy implementation, it is essential to involve multiple stakeholders, including departments, citizens, and planners. Encouraging citizens to provide feedback on their walking experiences through surveys and public participation activities can guide planning decisions. Additionally, policymakers should develop comprehensive management strategies to coordinate the efforts of relevant entities, ensuring the implementation of incremental updating policies. Regular assessments of walkability improvement measures should be conducted to enable timely adjustments and optimisations of these policies.

Furthermore, Python and ArcGIS platforms were used to digitalise the street space by combining multi-source data, such as road network data, POI data, and SVI. This research constructed a quantitative method to calculate the correlation mechanism between unobserved factors and street walkability, which provides a novel assessment approach for the analysis of the construction logic of the contemporary built environment.

Nevertheless, the following limitations need to be addressed. The results of the associated research are yet to be confirmed in terms of whether they will reveal similar results in other old town streets. From the perspective of the research content, this study focuses on the impact of the spatial form on walkability but has not considered pedestrians' perceived attitudes and walking behaviour. Owing to the limitation of data acquisition, the quantitative description of the walking space is insufficient, which may bring some bias to the results. Furthermore, some bias may be present in the findings due to the inevitable simplification or ignorance of intricate features in

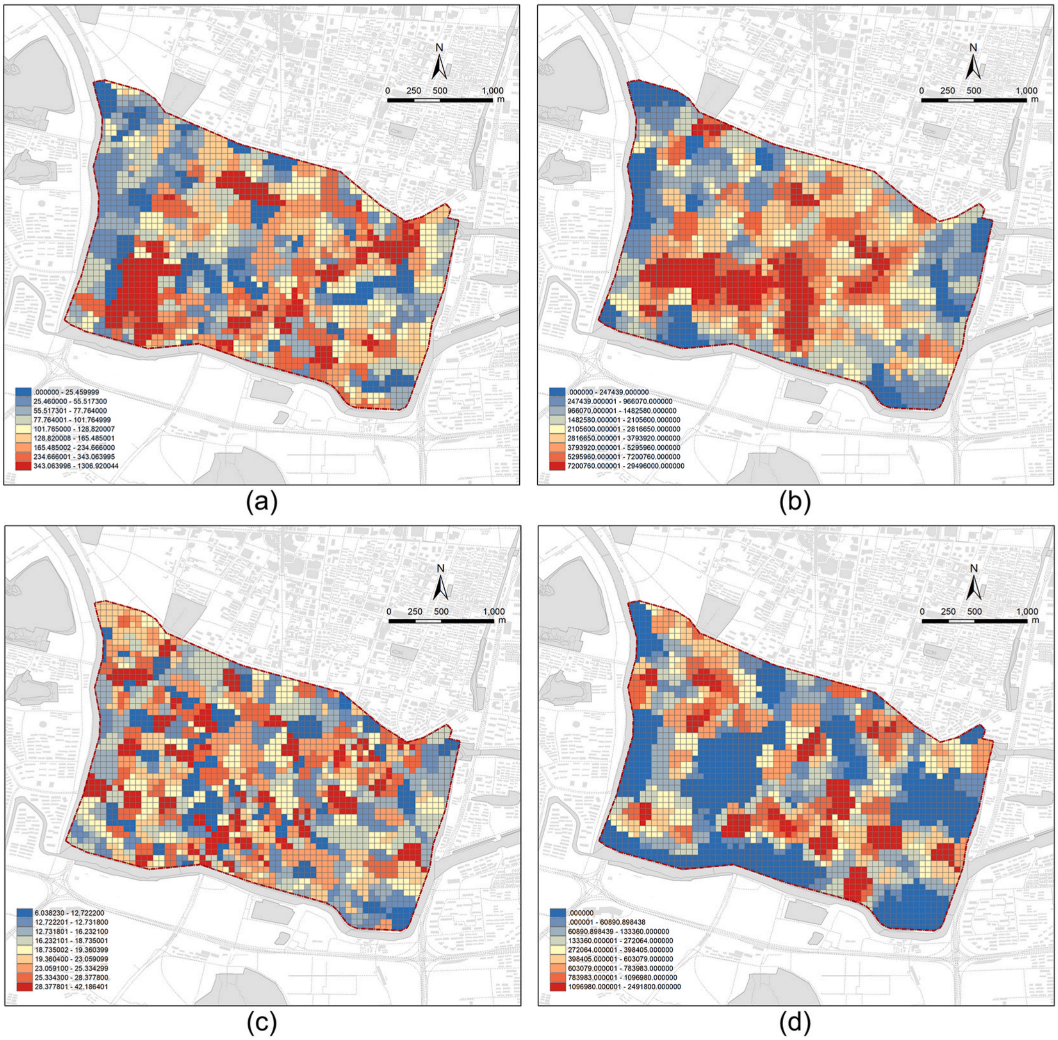


Fig. 11. The results of the observed factors of the convenience: (a) POI diversity; (b) POI density; (c) intersection density; (d) public transport density.

certain real circumstances that may occur throughout the process of quantifying unobserved factors and performing statistical procedures.

Combined with the current research progress, the following contents can be explored in depth: improve the construction of the theoretical model and compare the correlation of influencing factors under the guidance of various street functions and different construction periods. According to the spatial distribution results of walkability, as well as the correlation degree of 11 influencing factors and the low-value cluster area, the street space to be optimised can be further extracted so as to assist street space renewal in the decision-making process of design more accurately.

Data availability statement

Data will be made available on request.

Funding

This research was funded by the National Natural Science Foundation of China [grant number 52278051] and Postgraduate Research & Practice Innovation Program of Jiangsu Province [grant number KYCX22_0192].

CRediT authorship contribution statement

Xiao Han: Writing – original draft, Visualization, Software, Resources, Methodology, Funding acquisition, Conceptualization. **Zhe Li:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Yinyin Cao:** Validation, Software, Investigation, Data curation. **Zheng Zhou:** Validation, Software, Investigation, Data curation. **Hengyi Zhao:** Visualization, Software, Investigation, Formal analysis.

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.

References

[1] K. Lynch, The Image of the City, MIT Press, Cambridge, MA, USA, 1962.
[2] L. Anselin, I. Syabri, Y. Kho, Geo Da: an introduction to spatial data analysis, in: Handbook of Applied Spatial Analysis: Software Tools, Methods and Applications, Springer Berlin Heidelberg, Berlin, Heidelberg, 2010, pp. 73–89.
[3] J. Speck, Walkable city. Strauss and Giroux, Farrar, New York, 2012.
[4] J. Jacobs, The Death and Life of Great American Cities, Vintage, London, UK, 1992.
[5] J.T. Lang, Programs, paradigms, architecture, city planning, and urban design, J. Plan. Educ. Res. 5 (1985) 26–27.
[6] J. Wang, Inclusiveness and sharing, explicit and implicit mutual learning, livability predicted: historical prospect and contemporary creation of urban vitality, city plan, Rev. 43 (2019) 9–16.
[7] Y. Cao, X. Tang, Evaluating the effectiveness of community public open space renewal: a case study of the ruijin community, shanghai, Land 11 (2022) 476.
[8] Y. Tao, Y. Wang, X. Wang, G. Tian, S. Zhang, Measuring the correlation between human activity density and streetscape perceptions: an analysis based on Baidu street view images in Zhengzhou, China, Land 11 (2022) 400.
[9] M. Southworth, Designing the walkable city, J. Urban Plan, Dev 131 (2005) 246–257.
[10] A. Forsyth, What is a walkable place? The walkability debate in urban design, Urban Des, Int 20 (2015) 274–292.
[11] R.H. Lo, Walkability: what is it? J. Urban. 2 (2009) 145–166.
[12] D. Nabors, M. Gibbs, L. Sandt, S. Rocchi, E. Wilson, M. Lipinski, Pedestrian Road Safety Audit Guidelines and Prompt Lists, U.S. Department of Transportation, Federal Highway Administration, 2007. http://www.pedbikeinfo.org/cms/downloads/PedRSA.reduced.pdf.
[13] L.A. Wilson, B. Giles-Corti, G. Turrell, The association between objectively measured neighbourhood features and walking for transport in mid-aged adults, Local Environ. 17 (2) (2012) 131–146.
[14] J. Emery, C. Crump, P. Bors, Reliability and validity of two instruments designed to assess the walking and bicycling suitability of sidewalks and roads, Am. J. Health Promot. 18 (2003) 38–46.
[15] R. Ewing, S. Handy, Measuring the unmeasurable: urban design qualities related to walkability, J. Urban Des. 14 (2009) 65–84.
[16] P.N. Seneviratne, J.F. Morrall, Analysis of factors affecting the choice of route of pedestrian, Transp. Plan. Technol. 10 (1985) 147–159.
[17] M. Alfonzo, To walk or not to walk? The hierarchy of walking needs, Environ. Behav. 37 (2005) 808–836.
[18] U. Kim, J. Lee, S.Y. He, Pedestrianization impacts on air quality perceptions and environment satisfaction: the case of regenerated streets in downtown seoul, Int. J. Environ. Res. Public Health 18 (2021) 10225.
[19] M.H. Badland, Examining public open spaces by neighborhood-level walkability and deprivation, J. Phys. Act. Health 7 (7) (2010) 818–824.
[20] D.A. Rodríguez, E.M. Brisson, N. Estupiñán, The relationship between segment-level built environment attributes and pedestrian activity around Bogota's BRT stations, Transport. Res. Part D-Transport, Environ. Times 14 (7) (2009) 470–478.
[21] D.A. Rodríguez, R.K. Evenson, V.A. Diez Roux, S.J. Brines, Land use, residential density, and walking: the multi-ethnic study of atherosclerosis, Am. J. Prev. Med. 5 (2007) 397–404.
[22] J. Huang, X. Lu, J. Sellers, A global comparative analysis of urban form: applying spatial metrics and remote sensing, Landsc. Urban Plan. 82 (2007) 184–197.
[23] L.D. Frank, T.L. Schmid, J.F. Sallis, J. Chapman, B.E. Saelens, Linking objectively measured physical activity with objectively measured urban form: findings from SMARTRAQ, Am. J. Prev. Med. 28 (2) (2005) 117–125.
[24] K. Day, M. Boarnet, M. Alfonzo, A. Forsyth, The irvine–Minnesota inventory to measure built environments, Am. J. Prev. Med. 30 (2) (2006) 144–152.
[25] D. Rosenberg, D. Ding, J. Sallis, J. Kerr, G. Norman, N. Durant, S. Harris, B. Saelens, Neighborhood environment walkability scale for youth (NEWS-Y): reliability and relationship with physical activity, Prev. Med. 2 (2009) 213–218.
[26] K. Clifton, A. Smith, D. Rodriguez, The development and testing of an audit for the pedestrian environment, Landsc. Urban Plan. 1 (2007) 95–110.
[27] B. Saelens, L. Frank, C. Auffrey, R. Whitaker, H. Burdette, N. Colabianchi, Measuring physical environments of parks and playgrounds: EAPRS instrument development and inter-rater reliability, J. Phys. Act. Health 3 (s1) (2006) S190–S207.
[28] Front Seat, Walkscore, 2009. Available from: www.walkscore.com.
[29] F. Moura, P. Cambra, A. Gonçalves, Measuring walkability for distinct pedestrian groups with a participatory assessment method: a case study in Lisbon, Landsc. Urban Plan. 157 (2017) 282–296.
[30] M. Jabbari, F. Fonseca, R. Ramos, Combining multi-criteria and space syntax analysis to assess a pedestrian net-work: the case of Oporto, J. Urban Des. (2017) 1–19.
[31] C. Garau, A. Annunziata, Claudia Yamu, A walkability assessment tool coupling multi-criteria analysis and space syntax: the case study of Iglesias, Italy, Eur. Plan. Stud. 5 (2020) 1–23.
[32] F. Guan, Z. Fang, L. Wang, X. Zhang, H. Zhong, H. Huang, Modelling people's perceived scene complexity of real-world environments using street-view panoramas and open geodata, ISPRS J. Photogramm. 186 (2022) 315–331.
[33] F. Liang, J. Liu, M. Liu, J. Zeng, L. Yang, J. He, Scale-dependent impacts of urban morphology on commercial distribution: a case study of xi'an, China, Land 10 (2021) 170.
[34] A. Baobeid, M. Koç, S.G. Al-Ghamdi, Walkability and its relationships with health, sustainability, and livability: elements of physical environment and evaluation frameworks, front, Built. Environ. 7 (2021) 721218.
[35] P. Malambo, A.P. Kengne, A. De Villiers, E.V. Lambert, T. Puoane, Built environment, selected risk factors and major cardiovascular disease outcomes: a systematic review, PLoS One 11 (11) (2016) e0166846.
[36] L. Lin, A.V. Moudon, Objective versus subjective measures of the built environment, which are most effective in capturing associations with walking? Health Place 16 (2010) 339–348.
[37] X. Xu, N. Xu, W. Wang, X. Xu, Evaluation of Environmental Quality Elements for Vitality Generation of Backstreets and Alleys and its Remediation Strategy: A Case Study of Nanjing Old Town, Modern Urban Research, vol. 9, 2023, pp. 80–87.
[38] D.V. Dyck, G. Cardon, B. Deforche, I. De Bourdeaudhuij, Do adults like living in high-walkable neighborhoods? Associations of walkability parameters with neighborhood satisfaction and possible mediators, Health Place 4 (2011) 971–977.

[39] L. Frehlich, T.C. Turin, P.K. Doyle-Baker, J.J. Lang, G.R. McCormack, Mediation analysis of the associations between neighbourhood walkability and greenness, accelerometer-measured physical activity, and health-related fitness in urban dwelling Canadians, Prev. Med. 178 (2024) 107792.
[40] K. Manaugh, A. El-Geneidy, Validating walkability indices: how do different households respond to the walkability of their neighborhood? Transport. Res. D- Tr. E. 16 (2011) 309–315.
[41] R. Ewing, S. Handy, R.C. Brownson, O. Clemente, E. Winston, Identifying and measuring urban design qualities related to walkability, J. Phys. Act. Health 3 (2006) S223–S240.
[42] R. Talavera-Garcia, J.A. Soria-Lara Q-Plos, Developing an alternative walking index. A method based on urban design quality, Cities 45 (2015) 7–17.
[43] K.G. Moustaki, D. Joreskog, Marvidis, factor models for ordinal variables: a comparison of LISREL and IRT approaches, Struct. Equ. Modeling 11 (4) (2004) 487–513.
[44] J.Y. Hong, J.Y. Jeon, Influence of urban contexts on soundscape perceptions: a structural equation modeling approach, Landsc. Urban Plan. 141 (2015) 78–87.
[45] M. Said, M. Abou-Zeid, I. Kaysi, Modeling satisfaction with the walking environment: the case of an urban university neighborhood in a developing country, J. Urban plan, Dev 143 (2017) 05016009.
[46] N.A. Malek, M. Mariapan, M.K.M. Shariff, The making of a quality neighbourhood park: a path model approach, Procedia - Soc. Behav. Sci. 49 (2012) 202–214.
[47] S. Jaafari, A.A. Shabani, M. Moeinaddini, et al., Applying landscape metrics and structural equation modeling to predict the effect of urban green space on air pollution and respiratory mortality in Tehran, Environ. Monit. Assess. 192 (2020) 412.
[48] B. Bereitschaft, Equity in neighbourhood walkability? A comparative analysis of three large U.S. Cities, Local Environ. 22 (7) (2017) 859–879.
[49] Z. Li, X. Han, X.S. Lin, X.Y. Lu, Quantitative analysis of landscape efficacy based on structural equation modelling: empirical evidence from new Chinese style commercial streets, Alex. Eng. J. 60 (2021) 261–271.
[50] R.N. Mohanty, P.S. Chani, Assessment of pedestrians' travel experience at the religious city of puri using structural equation modelling, J. Urban Des. 25 (4) (2020) 486–504.
[51] Y. Hahm, H. Yoon, D. Jung, H. Kwon, Do built environments affect pedestrians' choices of walking routes in retail districts? A study with GPS experiments in hongdae retail district in Seoul, South Korea, Habitat Int. 70 (2017) 50–60.
[52] H. Xing, Y. Meng, Revealing deep semantic commercial patterns: insights from urban landscape depiction, Comput. Environ. Urban. 79 (2020) 101404.
[53] C. Fornell, A Second Generation of Multivariate Analyses: Volumes I. And II, Praeger Publishers, New York, USA, 1982.
[54] Y. Jin, From regression analysis to structural equation modeling: modeling linear causal relationships, Shandong Economy 2 (2008) 19–24.
[55] C. Samprit, S.S. Jeffrey, Handbook of Regression Analysis, John Wiley & Sons, Inc., Hoboken, New Jersey, 2013.
[56] L.S. David, Finding our way: an introduction to path analysis, Can. J. Psychiatr. 50 (2) (2005) 115–122.
[57] H. Doloi, K.C. Iyer, A. Sawhney, Structural equation model for assessing impacts of contractor's performance on project success, Int. J. Proj. Manag. 29 (6) (2011) 687–695.
[58] T. Sugiyama, M. Neuhaus, R. Cole, B. Giles-Corti, N. Owen, Destination and route attributes associated with adults' walking: a review, Med. Sci. Sport. Exer. 44 (2012) 1275–1286.
[59] J. Montgomery, Making a city: urbanity, vitality and urban design, J. Urban Des. 3 (1) (1998) 93–116.
[60] S. Doyle, A. Kelly-Schwartz, M. Schlossberg, J. Stockard, Active community environments and health: the relationship of walkable and safe communities to individual health, J. Am. Plann. Assoc. 72 (2006) 19–31.
[61] A. Turner, A. Penn, B. Hiller, An algorithmic definition of the axial map, Environ. Plann. B- Plann. Des. 32 (2005) 425–444.
[62] B. Hiller, Space Is the Machine: A Configurational Theory of Architecture, Cambridge University Press, 1996.
[63] T. Sun, B. Li, L. Zhang, S. Chen, S. Ji, Topological research on the spatial structure of Chinese traditional cities based on self-organizing theory, Urban Plann. Forum 1 (2019) 33–39.
[64] T. Hartig, R. Mitchell, S. De Vries, H. Frumkin, Nature and health, Annu. Rev. Publ. Health 35 (2014) 207–228.
[65] H. Frumkin, G.N. Bratman, S.J. Breslow, B. Cochran, P.H. Kahn Jr., J.J. Lawler, .S.A. Wood, Nature contact and human health: a research agenda, Environ. Health Persp. 125 (2017) 075001.
[66] G.N. Bratman, C.B. Anderson, M.G. Berman, B. Cochran, S. De Vries, J. Flanders, G.C. Daily, Nature and mental health: an ecosystem service perspective, Sci. Adv. 5 (2019) eaax0903.
[67] B. Jiang, C.Y. Chang, W.C. Sullivan, A dose of nature: tree cover, stress reduction, and gender differences, Landscape. Urban Plann. 132 (2014) 26–36.
[68] J. Rui, Measuring streetscape perceptions from driveways and sidewalks to inform pedestrian-oriented street renewal in düsseldorf, Cities (2023) 104472.
[69] W. Lin, C. Zeng, Z. Bao, H. Jin, The therapeutic look up: stress reduction and attention restoration vary according to the sky-leaf-trunk (SLT) ratio in canopy landscapes, Landsc. Urban Plann. 234 (2023) 104730.
[70] W. Xuan, K. Peng, C. Zang, Research on the correlation mechanism between street space quality and walking behavior in data environment, South Architecture 4 (2023) 49–60.
[71] Y. Ashihara, Translated by Lynne E. Riggs, the Aesthetic Townscape, The MIT Press, Cambridge, 1983.
[72] Z. Fang, K. Song, Q. Ye, Reflection of yoshinobu Ashihara's research about the proportion of street width to building height: a study of street space based on human scale, N. Archit. 5 (2014) 136–140.
[73] R.E. Park, E.W. Burgess, The City: Suggestions for Investigation of Human Behavior in the Urban Environment, The University of Chicago Press, Chicago and London, 1925.
[74] F. Lu, S. Tan, Urban form characteristics for walkable Neigborhood: a case study of 16 Neighborhoods in Nan'an district, Chongqing, Planners 35 (7) (2019) 69–76.
[75] M. Southworth, E. Ben-Joseph, Streets and the Shaping of Towns and Cities, Island Press, UK, 2006.