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Influencing factors of spatial vitality in underground space around railway stations: A case study in Shanghai

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ABSTRACT

Developing urban underground space for transportation and commercial purposes has become a vital strategy for sustainable urban growth, especially in dense urban contexts. The vitality of underground space has received wide attention as a key indicator of its efficiency and performance. The spatial vitality of underground space is affected by many factors, including function, spatial configuration, transport environment, and pedestrian-oriented design features. This study takes the underground space of Shanghai Hongqiao Business District (Phase I), one of the most successful integrated railway station-city development projects, as a case to explore the spatial and temporal distribution characteristics of spatial vitality and its influencing factors. Multilevel linear models were used to analyze the relationship between pedestrian flow and its influencing factors. Random forest models were used to investigate the relative importance of influencing factors on spatial vitality. This study verified that the distance to the transportation hub and spatial configurations calculated by space syntax are the two most essential factors for vitality. The number of retail stores and walkway width impact the vitality on weekends. The results shed light on our understanding of the urban vitality in the underground space and provide some tentative suggestions for the planning and design of underground space in high-density cities.

1. Introduction

1.1. Importance of spatial vitality in underground space

The development and utilization of underground space have been widely regarded as an effective method to solve many urban problems, especially in high-density urban areas (Admiraal, 2006; Edelenbos et al., 1998; Hunt et al., 2016; Sterling, 1997). The underground space provides habitable space for the city, relieving strain on supply and demand conflicts of urban land and space resources. Underground space also provides a comfortable, climate-resilient walking environment, reduces vehicle–pedestrian conflicts, and stimulates urban activities (Cui et al., 2013; Terranova, 2009).

The spatial vitality of underground space, indicating the level of vibrancy, activity, and usage of underground space, has aroused much attention recently (Ma et al., 2022; Xu & Chen, 2022). Evidence shows that spatial vitality greatly impacted the commercial conditions in underground space. For example, the commercial area of Flower City Square's underground space in Guangzhou's new city center reached 150,000 square meters in 2014. However, due to the low traffic and pedestrian flow, two-thirds of the shops had to be closed (Li et al., 2016). Also, spatial vitality is often unevenly distributed in underground spaces. Some passageways are packed with pedestrians, while others are empty. And even within the same passages, the usage situation changes over time (Li et al., 2016; Zhao et al., 2016). The usage of underground spaces varies from one area to another because of differences in their environmental quality, accessibility, functions, and so on. Worse, due to the lack of proper planning and design and imperfect management systems, many underground spaces often have problems such as poor accessibility and low spatial vitality (Qihu, 2016). Therefore, it is essential to find the influencing factors of the vitality of underground space at a fine-grained spatiotemporal scale because the construction of underground space is expensive and irreversible (Bobylev, 2009).

1.2. Underground space around railway stations

Although several studies have explored the influencing factors of spatial vitality of underground space around intra-city metro stations,

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the research in large-scale intercity railway stations (refer to railway station below), as far as we know, has received no attention. Developing underground spaces around railway stations is included as part of the integrated railway station-city development model in China, which has gained traction in recent years. The integrated station-city development model is an urban development concept that combines the basic principles of TOD theory with the environmental characteristics of Asian high-density cities (BIAN, 2014). In essence, the model believes that rail transit and cities could complement each other. Hence, a well-integrated development between rail transit and surrounding communities could achieve a vibrant, sustainable, healthy urban environment (BIAN, 2014). This approach allows cities to maximize their potential and create vibrant, interconnected hubs of activity. From economic and environmental perspectives, integrated station-city developments have proved to be effective, and numerous projects for constructing new cities and renovating existing ones are taking place (Liang et al., 2021). Among them, the Hongqiao transportation hub is a typical case, which is a major intermodal transport hub connecting one airport, one railway station, three metro lines, buses, and taxis. Hongqiao hub station-city development model has been followed by various other Chinese cities, e.g., Hangzhou, Guangzhou, and Shenzhen.

Hence, this study selected the 41,000 m^2 underground space in the Hongqiao transportation hub area as an example to explore its spatial vitality and the influencing factors.

1.3. Literature view

1.3.1. Definition and measurement of spatial vitality

As a crucial indicator of sustainable and healthy urban growth, spatial vitality has gained wide attention in urban planning and design, urban geography, urban economics, and many other fields (Liu et al., 2022; Wei et al., 2023). Many local governments have included it in their urban plan objectives (Chen et al., (2021b); Li et al., 2021). Urban spaces, e.g., streets, parks, and squares, are currently the primary focus of studies on spatial vitality (Guo et al., 2022; Jin et al., 2017; Lan et al., 2020). Lynch (1984) believes that urban space vitality derives from good urban form, and he defines it as the ability of an urban system to maintain its internal survival, growth, and development. He proposed four fundamental qualities of urban space vitality: sustenance, safety, unity, ecosystem diversity, and stability. Jacobs (1961) suggested that urban density, small blocks, diversified buildings, and mixed land uses are essential elements for urban space vitality. Alexander (2002) thought that a well-organized, legible urban structure and a wide variety of land use are characteristics of thriving cities. Urban space vitality is based on interactions between places and human activity. Although the concept of urban space vitality may differ among scholars, these concepts have pinpointed one converging feature: urban space vitality refers to the level to which an urban environment can attract, sustain, and stimulate various social and economic activities (Liu et al., 2022).

Urban space vitality can be quantified with either a single index or multiple indexes. The studies using a single index mainly concentrated on human activities or businesses. It includes pedestrian flow data, telephone survey data, mobile phone data, and big geographical data (Chen et al., 2022; Lan et al., 2020; Li et al., 2022). Jacobs-Crisioni et al. (2014) used mobile phone usage data to assess urban activity, finding that higher urban densities and diversified land uses are linked to higher activity levels. Long and Huang (2019) used social media data (Dianping and Weibo records) to assess urban economic vitality and found that urban design characteristics, including intersection density and level of mixed use, have a positive relationship with economic vitality. Ye et al. (2018) selected the small catering business in Shenzhen as a proxy for urban space vitality to examine how urban morphology and urban space vitality are related.

Other studies use multiple indexes to measure urban space vitality. Zeng et al. (2018) defined urban space vitality as four indexes, density, livability, accessibility, and diversity, to compare urban vitality in Chicago, USA, and Wuhan, China. Jin et al. (2017) applied three dimensions, including road junctions, points of interest (POIs), and location-based services (LBS) data based on human activity records, to evaluate the vitality of residential projects. In addition, some researchers have developed frameworks to assess urban space vitality, including the built environment, human activities, and human-environment interaction (Dong et al., 2021; Yue et al., 2019).

Underground space is part of urban space and similar to ground-level urban space in some ways. It also needs to accommodate various activities such as shopping, social interactions, and transportation. Although extensive studies have been done in the field of urban space vitality, quantitative research on the vitality of underground spaces remains relatively scarce. Pedestrian flow is usually used as an indicator to measure the vitality of the underground space (Ma et al., 2022; Ota et al., 2020; Sun & Leng, 2021; Xu & Chen, 2021; Xu & Chen, 2022; Zacharias, 2000; Zacharias & He, 2018). This is probably due to methodological considerations. Many big-data approaches to assess ground-level human activities, e.g., GPS tracking and mobile phone data, are unsuitable for the underground space (Chen et al., 2022; Liu et al., 2023). In addition, researchers usually define street vitality as the intensity of pedestrian flow or the complexity of types of activities on the streets (Li et al., 2022). Hence, this paper uses the pedestrian flow as the indicator to measure the vitality of the underground space.

1.3.2. Influencing factors of the vitality of underground space

The key influencing factors of the vitality of underground spaces can be summarized into four aspects: function, spatial configuration, transport environment, and pedestrian-oriented design features (Table 1). The function refers to services and facilities provided in an underground space. It is often assessed by the number of catering, shopping, and service facilities correlated with the pedestrian flow (Sun & Leng, 2021; Xu & Chen, 2022). Higher shop density will increase people's willingness to walk in the underground space (Zacharias & Wang, 2021), and the functional change of a site can also affect the redistribution of pedestrian flow (Zacharias, 2000). Certain functions, e.g., office, science, and education, are unrelated to spatial vitality (Ma et al., 2022).

The spatial configuration refers to the arrangement of different components within an underground space, including integration degree (evaluating the accessibility of target components), visibility (evaluating the visual accessibility of different components), and choice value (measuring the probability of a particular component being passed from one location to another). The space syntax method was often used to calculate the accessibility and visibility of different spatial components (Ma et al., 2022; Sun & Leng, 2021; Xu & Chen, 2021; Xu & Chen, 2022). Some studies reported that visibility to the transit station and adjacent facilities correlates to spatial vitality (Ota et al., 2020; Ota et al., 2018).

Table 1
Factors that affect the spatial vitality of the underground space.

Categories	Indicators	Methods
Function	Catering, shopping, service facilities, land use	POI, field survey
Spatial configuration	Local integration (R = 3), betweenness, visual step depth to the station, visual step depth to adjacent facilities, tenant count depth, metric shortest path to station, global integration value, visibility, choice value	Space syntax, SDNA
Transport environment	Transfer distance (total angle from the node to the destination), distance to metro stations, convenience of vertical facilities (elevators, stairs, and escalators)	Space syntax, field survey
Pedestrian-oriented design features	Walkway width, in shopping malls or not, spatial scale, illumination	Field survey

In addition, the location of the metro system, shopping malls, and office buildings can hugely influence the pedestrian flow and distribution in the underground space (Zacharias, 2000, 2015).

The transport environment refers to the degree to which a person can quickly reach a transit station from its location. It is often measured in two ways. First, the transport environment is often assessed by the distance and total angle from the target site to the metro station. The distance to transit stations negatively affects pedestrian flow, and people are often concentrated around a transit station because the transit station is the primary travel destination and origin (Ma et al., 2022; Xu & Chen, 2022). Furthermore, the total angle of turns from the point to the metro station also affects pedestrian flow because the excessive turns in the underground space will affect people's sense of orientation, resulting in difficulty in wayfinding and decreasing pedestrian flow. Second, the transport environment can also be assessed by the number of vertical facilities (including elevators, stairs, and escalators). Vertical transport facilities will increase pedestrian flow and spatial vitality by connecting underground and ground-level urban spaces (Xu & Chen, 2022).

As for the pedestrian-oriented design features, walkway width and spatial scale (width/height ratio) were positively correlated to spatial vitality (Zacharias & Wang, 2021). Wider walkways will increase people's willingness to walk in the underground space because wider walkways can increase pedestrian walking comfort (Zacharias & Wang, 2021). Furthermore, the ambient environmental factors, e.g., luminance, temperature, and wind speed, have already been explored, but only the illumination relates to the distribution of spatial vitality (Xu & Chen, 2022).

1.4. The research gap and our study

Although some studies have explored the influencing factors of underground space vitality, several research gaps need to be addressed. First, few studies consider four aspects of built environment factors simultaneously. Often, previous studies focus on one aspect or others, probably due to the small scale of study areas. While these studies point out the direction for further research, it remains unclear about the relative importance of different aspects of built environment factors in predicting urban vitality.

Second, previous studies mainly use correlation analysis or multiple regression models for data collected at different times of the day. Using several separate multiple regression models in one study will increase the risk of a Type I Error, which occurs when a researcher incorrectly rejects a true null hypothesis (Gelman & Hill, 2006). In addition, observational data collected at one location at multiple time periods tend to have autocorrelation, which violates the assumption of linear regression.

Third, most studies focused on the vitality of underground spaces near metro stations or shopping districts. To our knowledge, no study explores the underground vitality of large-scale integrated station-city development, which has gained increasing tractions in China. The underground space around railway stations differs from those around metro stations. First, the population composition is different, which may result in different travel demands. In the railway station area, people are brought by high-speed trains from other cities. A diverse population may have various travel demands in this area, and underground space usage may differ. Second, newly built railway stations are usually located in suburban areas or new towns, different from those metro stations in the established urban area. The population density and building density are lower in the area around railway stations compared with those metro stations. Thus, exploring how pedestrian flow is distributed in underground space around railway stations is crucial.

To address these problems, this study uses the underground space around the Hongqiao transportation hub area as an example to explore the influencing factors of spatial vitality in underground spaces. First, we develop a comprehensive framework for measuring different aspects of built environment features in underground space. Second, we use the multilevel linear model to address the autocorrelation present in the data and analyze the influencing factors of spatial vitality on weekdays and weekends. Third, we apply random forest models to examine the relative importance of different influencing factors on spatial vitality. In summary, this study aims to explore the influencing factors of spatial vitality and the relative importance of different factors in underground space around the Hongqiao transportation hub area.

2. Methodology

2.1. Study area

Hongqiao Hub is a comprehensive transportation hub comprising Hongqiao Airport, Hongqiao High-speed Railway Station, and three metro lines (Line 2,10,17) in Shanghai, China (Fig. 1a). On the west side of the Hub, one business district of 1.4 km^2 land area, Hongqiao Business District (Phase I), started to be built in 2011 (Fig. 1b). A network of underground space is under the business district, connecting the Hongqiao Hub on the east side, and the National Exhibition and Convention Center on the west side. The excellent location and convenient walking environment have brought a vast and stable passenger flow to the underground space. This underground network integrates businesses, offices, hotels, cultural entertainment, exhibitions, and other urban functions, including Hongqiao Vanke Center, Hongqiao TianDi, Hongqiao Vantone Center, Longfor Hongqiao Paradise Walk, Lihpao Plaza, and other commercial complexes.

The study area is mainly located on the underground floor as shown in Fig. 1c. This synthetic development of railway stations and cities includes one underground central axis passage, two sunken plazas (Vanke Center and North District of TianDi), three underground commercial facilities (South District of TianDi, Longfor Paradise Walk and Lihpao Plaza) and some minor underground passages. The underground central axis passage becomes the dominant public space, and the entire underground space has an area of approximately 41,000 m^2.

2.2. Pedestrian data

The pedestrian flow data was used as the indicator of spatial vitality in the underground space. We collected the pedestrian flow data of each underground segment with the cordon counts method. This method counts all people who cross a defined line or segment in both directions in a specific amount of time. It is an objective method and has been widely used to collect pedestrian flow data in underground space studies (Ma et al., 2022; Zacharias & He, 2018).

Eighteen underground segments that reflect the daily pedestrian flows in the underground space were chosen to collect data, as shown in Fig. 1. These segments are mainly the segments of entrances and exits leading to major shopping malls, office buildings, metro stations, and the ground. They are places where the changes in pedestrian flow are most obvious, concentrated, and representative.

Before we collected the pedestrian flow data in the main survey (on May 20 and 22, 2021), we conducted a pre-survey for about 70% of underground segments (on May 13 and 15, 2021) to ensure the reliability of the data collection process and avoid errors. The pedestrian flow data collected in the pre-survey were similar to those collected in the main survey ($p < 0.05$). Therefore, the pedestrian flow data measured in the main survey was reliable. The main survey data was collected on one weekday and one weekend in 2021. Both days were not holidays, and the weather was sunny. The outdoor temperature is within 16-23℃, suitable for outdoor activities. The COVID-19 pandemic was well-controlled in Shanghai in 2021. According to relevant data released by the Shanghai Hongqiao Management Committee website, the average daily passenger flow of Hongqiao Hub in 2021 has recovered to about 80% of the pre-epidemic level in 2019.

From 8:30 am to 8:30 pm, cordon counts were conducted once an hour and twelve times daily to cover peak and non-peak hours, with the

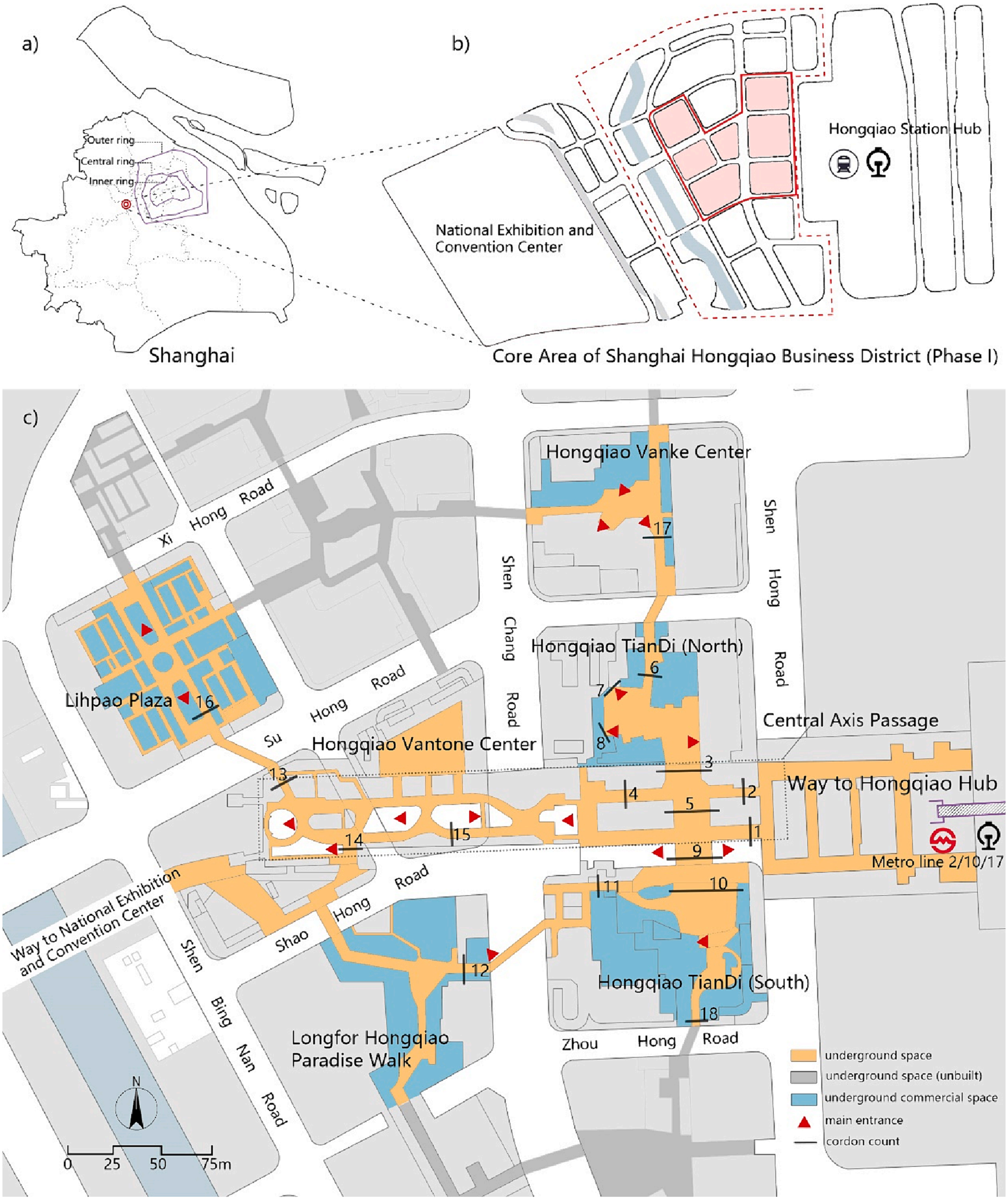

Fig. 1. a) Location of Hongqiao Hub in Shanghai. b) Shanghai Hongqiao central business district (Phase I) and the study area in it. c) The underground space in the Hongqiao hub station area.

help of nine research assistants with adequate training. The ten-minute pedestrian flow was recorded each hour at each segment, so the total data collecting time is 4320 mins (i.e., two days *12 h *18 segments *10 mins).

2.3. Influencing factors

According to previous studies, the pedestrian flow is affected by four types of influencing factors, as shown in Table 2, which are function, spatial configuration, transport environment, and pedestrian-oriented

Table 2
Influencing factors of spatial vitality in underground space.

Categories	Variables	Description
Function	POIs in retail, residential, office, recreational, catering	Number of POIs within walking distance of 50 m
	Land use mix	The degree of mix of land use functions
Spatial configuration	Integration (200 m, 400 m, 600 m, 800 m, 1000 m)	Accessibility, local integration with a radius from 200 m to 1000 m in Line Segment Map Model
	Visual integration	The visual accessibility in Visibility Graph Analysis Model
Transport environment	Bus stops	Number and distance of bus stops nearby
	Distance and turns to the Hongqiao Transportation Hub	The walking distance and number of turns from the Hongqiao Transportation Hub
	Vertical facilities	Number and distance of vertical facilities nearby
Pedestrian-oriented design features	Resting seats	Resting seats in the segments or not
	Walkway width	Walkway width at different segments (m)
	Whether inside a shopping mall or not	The selected segments whether in a shopping mall or not

design features (Cui et al., 2013; Cui et al., 2015; Dong et al., 2021; Ma et al., 2022; Sun & Leng, 2021; Xu & Chen, 2022; Zacharias, 2000).

2.3.1. Function

Number of POIs

Point of Interest (POI) is a term in geographic information systems that generally refers to all geographic objects that can be abstracted as points, primarily some geographic entities closely related to people's lives, such as schools, banks, restaurants, gas stations, etc. The distribution of pedestrian flow is usually affected by different functions (such as catering, office, parent–child activities, etc.). These functional points can be displayed on the map through POIs (Sun & Leng, 2021; Xu & Chen, 2021).

In this paper, the POI data was obtained from the Gaode Map. Its categories included retail, residential, office, recreational, and catering, which are closely related to people's activities in the study area. Field investigations were also conducted to verify the distribution and position information of the POIs. The variables were the number of POIs in each category within walking distance of 50 m from each underground segment pedestrian, following previous studies (Ota et al., 2020; Sun & Leng, 2021).

Land use mix

Land use mix measured the degree of mix of land use. Diverse land use has long been considered essential to urban vitality (Jacobs, 1961). The degree of the mix of urban function has frequently been assessed using the entropy of the POIs (Cervero & Kockelman, 1997; Jiang et al., 2021). It is calculated by Eq. (1).

$$H(x) = -\sum_{i=1}^{n} P_i \log P_i \quad (1)$$

where $H(x)$ represents the entropy of the random variable X. P_i is the probability that X takes X_i. The larger the entropy value, the higher degree of land mixing.

2.3.2. Spatial configuration

Space syntax is used for measuring spatial configuration. It is a theory of space and a series of descriptive methods for quantitative analysis of buildings and urban spaces (Hillier, 2007). Using the variables associated with complex spatial patterns in buildings and cities, space syntax is suitable for revealing social causes and consequences of physical spatial patterns. It is widely used in the analysis of architecture and urban fields and has also been applied in urban underground space research (Ota et al., 2018; van der Hoeven & van Nes, 2014; Xu & Chen, 2022).

Space syntax methods, which are related to spatial vitality, usually include visibility and accessibility. In this paper, the software DepthmapX0.6 (Team, 2017) was applied to build a Line Segment Map model to analyze the accessibility of the underground space and a Visibility Graph Analysis model to calculate the visual accessibility of the underground space.

Integration

The accessibility of the underground space was measured by the integration variable in the Line Segment Map model in terms of the topological depth of a component (i.e., passageway segment in this study) in a graph system according to space syntax theory (Hillier, 2007). Both local integration and global integration can be considered. Local integration measures the topological depth from one component to all components with a particular distance to the component (e.g., 200 m). In contrast, global integration considers all other system components regardless of distance. According to previous studies, local integration with a radius from 200 m to 1000 m was selected for the analysis with DepthmapX0.6 (Xu & Chen, 2021).

Visual Integration

The visual accessibility of the underground space was measured by the visual integration variable in the Visibility Graph Analysis model in terms of the visual depth of a component in a system (Fig. 2). A higher value of visual integration means that this element needs to make fewer turns to see other elements in the system, that is, better visual accessibility it will be (Hillier & Hanson, 1984). In the Visibility Graph Analysis model, the grid is set to 1 m*1 m, which is an appropriate grid density to analyze the pedestrian flow in the underground space (Xu & Chen, 2021). The parameter of the maximum line-of-sight distance in the model is set to infinity (i.e., the default value) instead of a specific distance (e.g., 200 or 300 m) because the multiple turns and narrow corridors in an underground space often block lines of sight and shorten the distance even with the parameter of infinity.

2.3.3. Transport environment

According to Cui et al.'s research in three metro station underground spaces (People's Square, Jing'an Temple, Xujiahui) in Shanghai (Cui et al., 2015), the majority of respondents reached urban underground space by transit (68.2%), followed by walking (15.4%), and bus (11.5%). Thus, we mainly consider three transportation variables: bus stops, distance to the Hub, and vertical transport facilities (lifts and

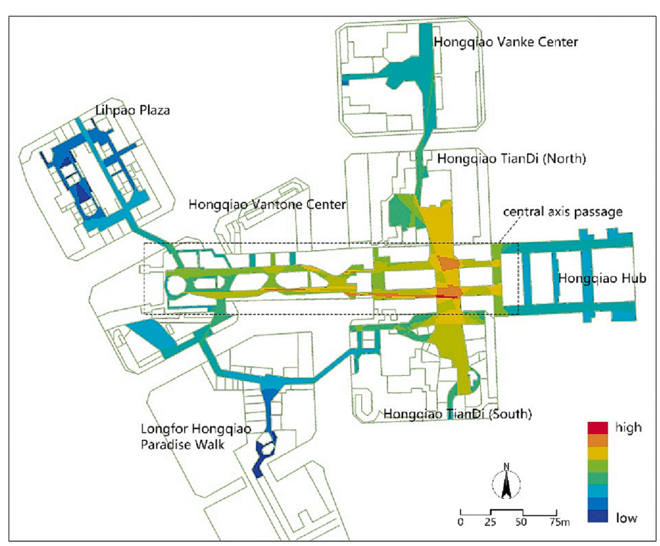

Fig. 2. Results of the visual accessibility in the underground space.

staircases).

Bus stops

Generally, more bus stops and closer distance lead to greater pedestrian flow (Sun & Leng, 2021; Xu & Chen, 2021). Considering the distance decay effect, we will use the inverse distance weighting method (IDW) to evaluate the bus stop parameter, which has been widely used in other studies (Lu & Wong, 2008; Shukla et al., 2020). The parameter of the bus stop in each segment will be calculated as a summation of the product of "weight" and "value". The weight formula is 1/distance, where distance measures the straight-line distance from bus stops to the selected segments. The value of each bus stop is assigned the same. Hence, greater weight will be assigned to the bus stops near the selected segments.

Distance and turns to the Hongqiao Transportation Hub

The walking distance and number of turns from the Hongqiao Transportation Hub to different destinations may affect the distribution of the pedestrian flow because the Hub is this underground space's primary origin or destination. Both the physical distance and the number of turns were measured in this study.

Vertical facilities

The layout of vertical facilities, including escalators, elevators, and stairs, impacts the pedestrian flow (Zhuang et al., 2014). In this study, the factor of vertical facilities will also be assessed by the inverse distance weighting method (IDW). The weight formula is 1/distance, and the value of each vertical facility is assigned the same.

2.3.4. Pedestrian-oriented design features

Pedestrian-oriented design features generally promote people's propensity to walk in urban and underground spaces (Cervero & Kockelman, 1997; Zacharias & Wang, 2021). In this study, three design characteristics of the underground space were measured.

Resting seats

The presence of resting seats is effective in promoting walking behavior and spatial vitality on urban streets and underground spaces (Kang, 2018; Xu & Chen, 2022). This paper sets the value of 1 for public seats near the cordon count location and 0 for the others.

Walkway width

The walkway width has been verified as an important factor in pedestrian comfort in underground spaces (Zacharias & Wang, 2021). Walkway width was measured in each sampled segment.

Whether inside a shopping mall or not

Some walkways pass through a shopping mall in the study area, and they may have excessive pedestrian flow because some pedestrians may visit the shopping mall on purpose. If the sampled segment was inside a shopping mall, it was set to 1. If not, then the value was 0.

2.4. Statistical analysis

2.4.1. Spatial and temporal distribution of pedestrian flow

First, we used paired t-test to examine the difference of the average pedestrian flow between weekdays and weekends. The average pedestrian flow data at each underground segment on both weekdays and weekends was used to analyze the spatial distribution of pedestrian flow. All segments' hourly average pedestrian flow (person/hour) data was used to compare the temporal distribution of pedestrian flow on weekdays and weekends.

2.4.2. Multilevel linear models

Multilevel linear models were applied to investigate the relationship between spatial vitality and its influencing factors. Multilevel linear models can account for the clustering data structure problem, e.g., data collected at different times is nested in a place (Finch et al., 2019) and simultaneously address the inflated Type I error issue. It has already been proven to be helpful in various studies to solve the problem of data interdependence and clustering (Lu, 2019; Zang et al., 2019). The multilevel linear model includes both fixed effects and random effects. The cordon count sites were assigned to a random effect that accounts for the clustering of 12 pedestrian flow data of a day at each cordon count site, considering that some cordon count sites may always have higher pedestrian flow than others. The effects of time periods were assigned to another random effect accounting for the temporal variation of pedestrian flow. The influencing factors of four categories listed in Table 2 were assigned to the fixed effects, and the variables of resting seats and inside a shopping mall were set to be the dummy variables. The multilevel linear model was as Eq. (2). The variance inflation factors (VIF) were used to check the multicollinearity problem between those variables in the model. We retained the variables with VIF < 4 in the model, similar to the selection criterion in previous studies (Ma & Dill, 2015; Zang et al., 2019). The intraclass correlation coefficient (ICC) was reported to estimate the proportion of the variance that can explained by its clustering structure. The ICC is the proportion of explained variance that can be attributed to the random effects (Hox et al., 2017). The conditional R^2 was also reported to reflect the variance of the outcome explained by the fixed and random effects.

$$Y_{ijk} = \beta_0 + \beta_1 x_{ijk} + \mu_j + u_k + \varepsilon_{ijk} \tag{2}$$

where Y_{ijk} is the pedestrian flow i in different cordon count sites j and different time periods k. β_0 is the common intercept. x_{ijk} is a set of explanatory variables in Table 2 (fixed effects). β_1 are the regression estimated coefficients for different variables x_{ijk}. μ_j is the random effect of different cordon count sites j. u_k is the random effect of different time periods k. ε_{ijk} is the error term of the regression model.

All analyses were conducted in R with the multilevel lme4 package (Finch et al., 2019).

2.4.3. Random forest models

In this step, we further analyzed the relative importance of different influencing factors of spatial vitality using the random forest approach. Random forests are an ensemble learning method for regression and classification (Breiman, 2001). Random forest models use the bootstrap resampling method to select a fixed number of sample sets from the entire training sample set and then select a fixed number of feature sets to construct lots of decision trees to form a random forest. The final result of a random forest model is calculated by the average value of predictions from all trees (Cutler et al., 2007). Random forest models are insensitive to multicollinearity, and their results are relatively robust to missing and unbalanced data. In addition, it performs well in analyzing data with small sample sizes (Chen et al., (2021a)).

In a random forest, each decision tree is generated randomly by sampling with replacement about two-thirds of the training data and leaving the other third untrained (training data bagging). The final forest is created using majority vote (classification) or the average prediction of all trees (regression). At the same time, one-third of the data retained on each tree can be used to calculate a performance evaluation metric, namely the Out of Bag (OOB) error estimate (Breiman, 2001). Thus, the OOB error provides a simple way to adjust the parameters of the model without requiring a validation set (Biau & Scornet, 2016).

The OOB error can be used to estimate the importance of each variable. The most widely used way to estimate relative importance is the increase in the Mean Square Error (%IncMSE) (Genuer et al., 2010; Grekousis et al., 2022). This method randomly permutes the value of each variable in the OOB sample and calculates the OOB error. If the OOB error grows with the permuted values, it shows that the variable is significant. The larger the change, the more important the variable is. Two critical parameters in the random forest model linking to OOB error are the number of trees in the forest (n_{tree}) and the number of variables in each tree (m_{try}) (Liaw & Wiener, 2002). The n_{tree} is set as a trade-off between computational complexity and accuracy (Biau & Scornet, 2016). The m_{try} is decided by the minimization of the OOB error (Georganos et al., 2021). We tested the model with the number of trees (n_{tree}) from 100 to 1000 with an interval of 20 to get the optimal random forest model (Cheng et al., 2020). It was found that the OOB error started to become stable when more than 500 trees were built. Therefore, the number of trees (n_{tree}) was set to 500. Then, we tried different numbers of splitting variables (m_{try}) (1, 2, 3…n, n = number of variables) to choose the minimization of the OOB error (Cheng et al., 2019). The results showed that the best prediction model of pedestrian flow on weekdays is when $n_{tree} = 500$ and $m_{try} = 2$, while for weekends, it is when $n_{tree} = 500$ and $m_{try} = 3$. With these parameters, we conducted the variable importance testing. All the random forest analyses were implemented with the package randomForest in R (Team, 2009).

3. Results

The results showed that the distribution of pedestrian flow differs significantly between weekdays and weekends (Fig. 3). According to the paired t-test, the difference is significant ($t = 6.21$, $p < 0.001$). Generally, weekday pedestrian flow was 40% higher than weekends' in most counting sites. It was similar to the phenomena in North American cities, Toronto, Minneapolis, and Houston, where there are many activities on weekdays and fewer on weekends throughout the CBD (Byers, 1998). However, this was contrary to the cases in some Chinese cities, including the Yuantong area in Nanjing and the Wujiaochang area in Shanghai (Ma et al., 2022; Sun & Leng, 2021), which are located in the city center areas. The underground space in this study was located in a suburban area and may have a different usage pattern than those in city centers.

3.1. Spatial distribution of pedestrian flow

Overall, the spatial distribution of pedestrian flow in the underground space was uneven on weekdays or weekends (Figs. 4 and 5). The pedestrian flow was relatively high among the three locations near the Hongqiao Hub (Hongqiao Vanke Center, Hongqiao TianDi), and the distribution of pedestrian flow in other places was relatively low. The average pedestrian flow, whichexceeds 600 persons/hour, was mainly distributed within 400 m from the Hongqiao Hub (Fig. 6). It is similar to the findings gained by Xu and Chen (2022) in Shanghai, where the pedestrian flow was highly concentrated around the transportation hub.

The pedestrian flow on the north side was about 55% higher on weekdays than on weekends; the pedestrian flow on the south side was about 25% higher. The relatively small change in pedestrian flow on the south side was mainly due to the presence of two major shopping malls, Hongqiao TianDi Shopping Center and Longfor Hongqiao Paradise Walk (Fig. 4). These commercial areas attracted many people for entertainment and shopping, both on weekdays and weekends. Hence, the pedestrian flow was stable on both weekdays and weekends. However, on the north side, most destinations were offices. There was no major shopping mall. So, there was a steep drop in pedestrian flow on weekends compared to weekdays.

3.2. Temporal distribution of pedestrian flow

Fig. 7 shows the hourly distribution of pedestrian flow at each segment. On weekdays, the pedestrian flow was relatively high in three time periods (9:00, 12:00–13:00, 18:00–19:00). It reflected that many people commute in the morning and evening and go out during lunchtime in the underground space. The result echoes one previous study with a minor difference, where there were three peak times (7:00–9:00, 11:00–13:00, 17:00–19:00) in urban underground places of city centers in Shanghai (Xu & Chen, 2022).

On weekends, the pedestrian flow gradually increased before 13:00 and gradually decreased after 18:00. The pedestrian flow plateaus between 13:00 and 18:00, with a minor drop. This reflected the fact that people come here mainly for entertainment and leisure during the afternoon. Hence, the difference in the temporal changes of the pedestrian flow on weekdays and weekends reveals the temporal heterogeneity in the underground space usage.

3.3. Results of multilevel linear regression

The coefficients of influencing factors of spatial vitality on weekdays and weekends are shown in Table 3. All variables were checked for multicollinearity with the variance inflation factors (VIF) test. Variables with VIF > 4, including recreational, catering, land use mix, integration (400 m, 600 m, 800 m, 1000 m), visibility integration, bus stops, turns to the Hongqiao Hub, resting seats, and inside a shopping mall, were removed from the models. The conditional R^2 values revealed that the combination of all variables accounts for 90.9% of the variance in the pedestrian flow on weekdays and 92.7% of the variance on weekends. The results showed that the intraclass correlation coefficient (ICC) is 0.348 and 0.224 for the model of weekdays and weekends respectively, indicating that 34.8% and 22.4% of variation can be attributed to the clustering structure of our data on weekdays and weekends respectively.

Overall, on weekdays, two factors significantly influenced the pedestrian flow—integration (200 m) and distance to the Hongqiao Transportation Hub; on weekends, four factors significantly influenced the pedestrian flow—retail, integration (200 m), distance to the Hongqiao Transportation Hub and walkway width.

The difference in influencing factors on weekdays and weekends indicates the different usage patterns in the underground space. The weekdays are mainly for transferring and commuting, while weekends are mainly for shopping and leisure.

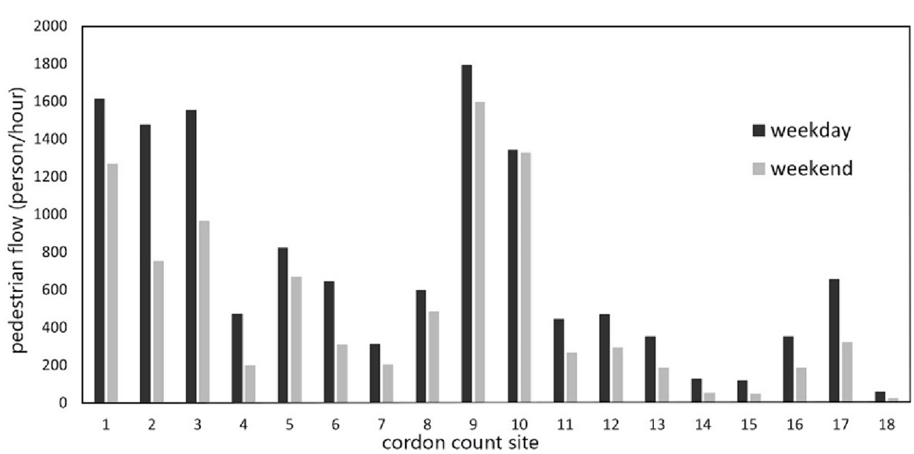

Fig. 3. Pedestrian flow of each cordon site on weekdays and weekends.

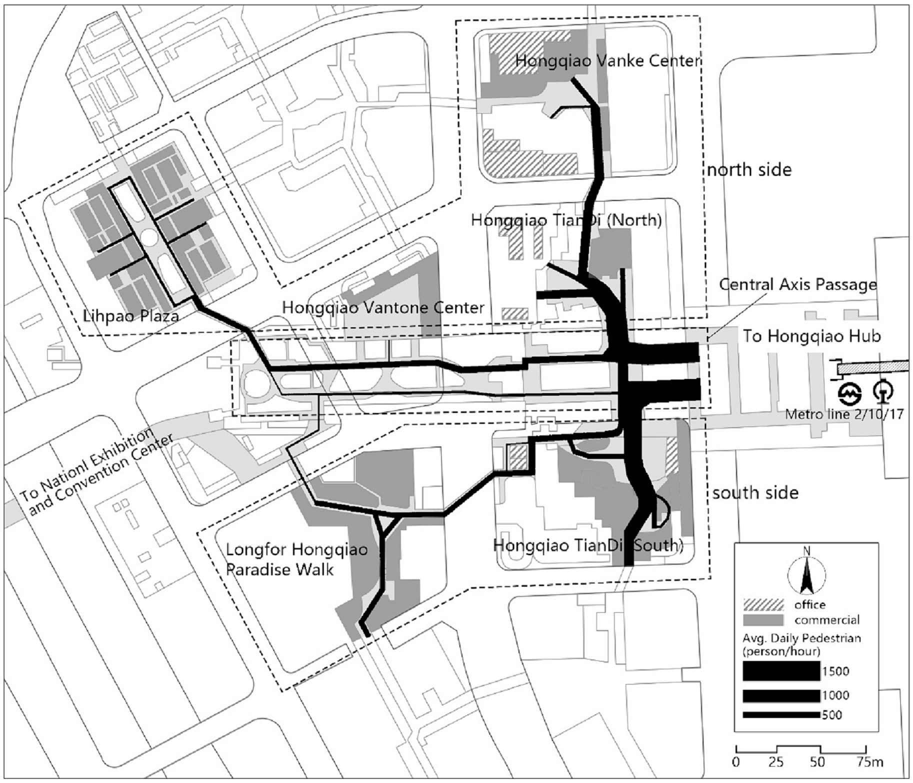

Fig. 4. Spatial distribution of pedestrian flow on weekdays.

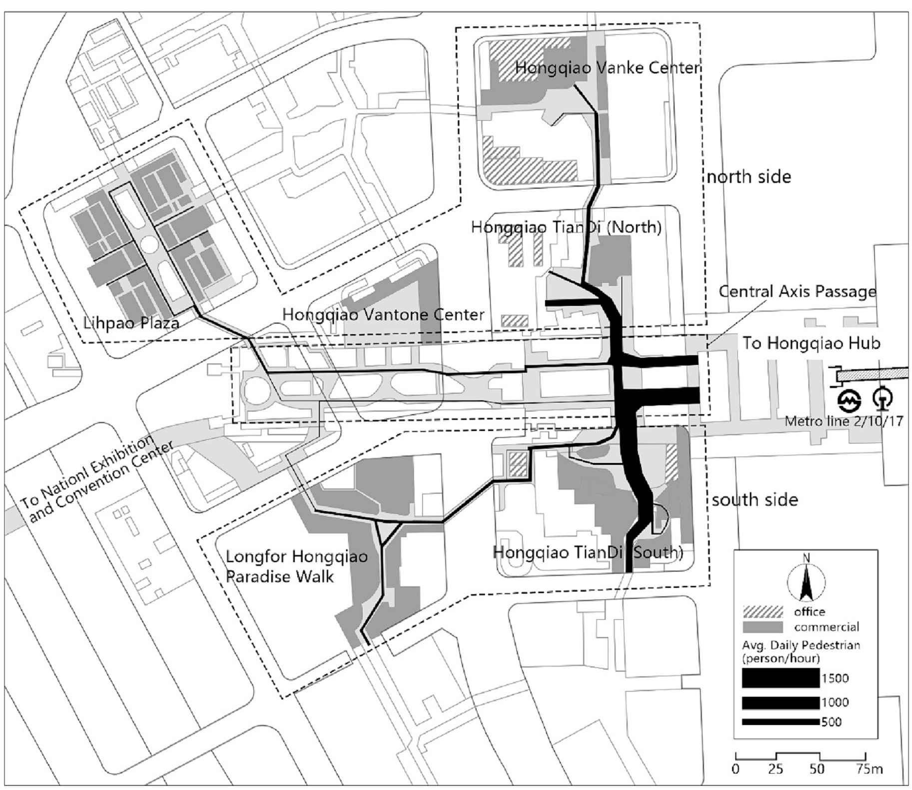

Fig. 5. Spatial distribution of pedestrian flow on weekends.

3.4. Relative importance of associated explanatory variables

The relative importance of different variables was tested in the random forest models, shown in Fig. 8. The variables used in the random forest models were the same as those used in the multilevel linear models. The percentage of variance explained on weekends (76.94%)

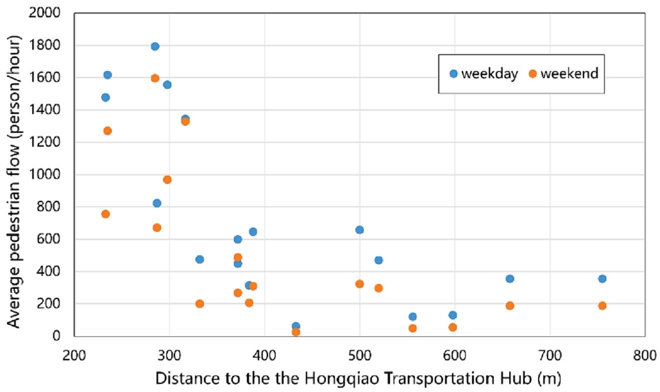

Fig. 6. Average pedestrian flow of each cordon site at different distances to the Hongqiao Hub.

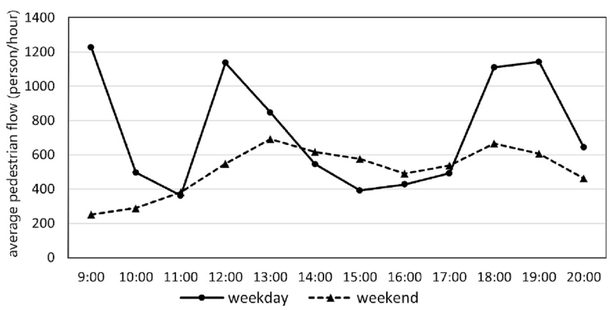

Fig. 7. Temporal distribution of pedestrian flow on weekdays and weekends.

Table 3
Multilevel linear regression analysis to predict influencing factors of spatial vitality.

Model predictors	Weekdays β (95 %CI)	p-value	Weekends β (95 %CI)	p-value
Functional layout				
Retail	0.256 (-0.021, 0.535)	0.056	0.357 (0.046, 0.671)	0.017*
Residential	0.173 (-0.091, 0.437)	0.174	0.101 (-0.195, 0.397)	0.480
Office	0.067 (-0.245, 0.379)	0.656	−0.053 (-0.403, 0.298)	0.755
Spatial configuration				
Integration (200 m)	0.482 (0.080, 0.886)	0.013*	0.461 (0.008, 0.916)	0.036*
Pedestrian traffic environment				
Distance to the Hongqiao Transportation Hub (shortest-path length)	−0.528 (-0.812, −0.243)	< 0.001***	−0.568 (-0.887, −0.248)	< 0.001***
Number and distance of vertical facilities nearby	0.229 (-0.101, 0.561)	0.152	0.341 (-0.030, 0.715)	0.059
Space design features				
Walkway width	0.232 (-0.123, 0.588)	0.176	0.399 (0.001, 0.799)	0.039*
Constant	4.340	< 0.001***	3.901	< 0.001***
Conditional R^2	0.909		0.927	
ICC (Intraclass correlation coefficient)	0.348		0.224	

Note: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, β: standardized coefficient.

was higher than on weekdays (46.94%), similar to those in the multilevel linear models.

Distance to the Hongqiao Transportation Hub was the most critical variable with a contribution of 25.41% and 28.94% on weekdays and weekends, respectively. Walkway width, integration (200 m), and vertical facilities were ranked second to fourth on weekdays and weekends, with contributions more than 13%. Among the functional layout variables, office was the most important variable in predicting pedestrian flow, accounting for 12.97% (weekdays) and 12.39% (weekends) of the total effect. Residential function contributed the least on weekdays and weekends.

4. Discussion

4.1. Major findings

Attracting adequate pedestrian flow is critical to economic success and sustainable underground space development. Previous evidence suggests that pedestrian flow in underground space is affected by four aspects of built environment factors: function, spatial configuration, transport environment, and pedestrian-oriented design features. However, few studies simultaneously consider four aspects of built environment factors and point out the relative importance of different factors. Also, few studies considered the clustering data structure problem when conducting analysis, and the underground space within the railway station area was rarely studied. In this study, we analyzed the influencing factors of spatial vitality in the underground space around Shanghai Hongqiao Transportation Hub, a multi-modal railway station. We obtained five major findings using the multilevel linear and random forest models.

First, distance to the Hongqiao Transportation Hub was significant on both regression models of weekdays and weekends. This variable is also the most important variable on weekdays and weekends. It is similar to the results by Ota et al. (2018) in Nagoya Station Underground Mall and Ma et al. (2022) in Jiangwan–Wujiaochang Sub-center. Hongqiao Transportation Hub brings many people to the underground space as a main generator of pedestrians. Generally, the closer to the hub, the more convenient transportation and commuting, and the more people will be; the farther away from the metro and railway exit, the fewer people will be (Zacharias, 2007), and the less willingness of people to walk (Zacharias & Wang, 2021). Therefore, it is necessary to rationally arrange underground space around the transportation hubs, either railway stations or metro stations, to improve the distribution of the pedestrian flow in the underground space.

Second, walkway width correlated to the pedestrian flow on weekends. Other studies reported similar results (Ma et al., 2022; Xu & Chen, 2022). The walkway width can enhance people's positive experience of the underground space, and wide and well-lit walkways will encourage more people to use it (Zacharias & Wang, 2021). However, walkway width does not affect pedestrian flow on weekdays. The difference between weekends and weekdays may be explained by different travel demands in two time periods. People in this underground space mainly conduct shopping and leisure activities on weekends. Therefore, they are more receptive to the surrounding environment, including walkway width. On weekdays, however, people mainly use this space to commute, and the travel distance or time plays a more significant role in the path selection than walkway width.

Third, the number of retail stores significantly influences the pedestrian flow on weekends. The finding was similar to one study conducted in Yuantong district, Nanjing city, by Sun and Leng (2021), in which shopping is correlated to pedestrian flow on weekends but not on weekdays. Also, another study by Zacharias and Wang (2021) shows that people will be more willing to walk in the underground space with more shops. Many people may visit the underground space for commercial purposes, especially on weekends (Cui et al., 2015). However, we also found that the number of retail stores is not linked to pedestrian

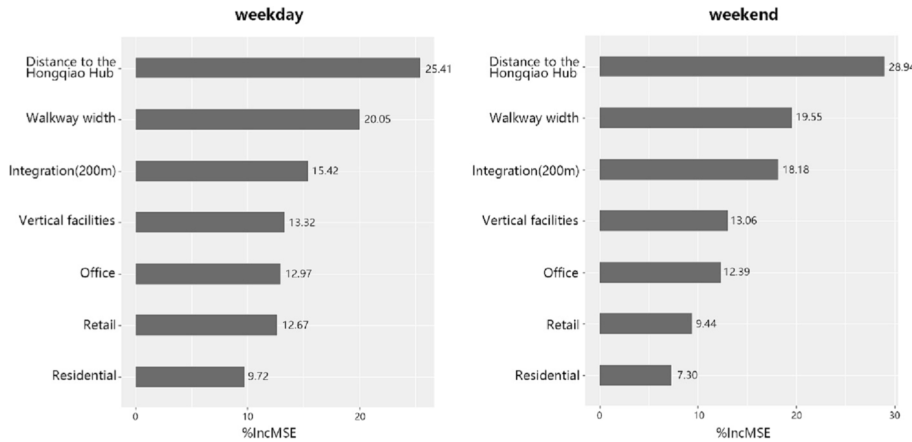

Fig. 8. Relative importance of the explanatory variables on weekdays and weekends.

flow on weekdays. It reveals that the shopping activities were overtaken by commuting on weekdays as the total office space area is 35% more than that of commercial space.

Fourth, the office POIs have higher relative importance than the variable of retail in predicting pedestrian flow, as revealed by the random forest model, though it was insignificant in the multilevel linear model. The result is in line with previous evidence (Zacharias, 2000, 2007). As a primary generator of pedestrians, the office buildings often generate a large pedestrian flow, and the change of office district will result in a redistribution of pedestrians (Zacharias, 2000, 2007). In this study area, many office buildings similarly affect the distribution of pedestrian flow in the underground space as a major destination or origin during peak hours.

Fifth, this research combined the strengths of multilevel regression and random forest models, further contributing to the methodological development of underground space vitality studies. The random forest model revealed the relative importance of different variables on weekdays and weekends. It further verified the results of multilevel linear models, although there are some disparities between the results of the two models. Previous research has also shown a similar difference between the multilevel linear regression and random forest models (Jiang et al., 2022; Pahlavan-Rad et al., 2020). Linear or logistic regressions are preferred by researchers because they are straightforward to calculate and comprehend (Smith et al., 2013), but they run the risk of oversimplifying the complicated relationship between the built environment and spatial vitality. The random forest method is more sophisticated than linear and logistic regression models and has better predictive power. It also has certain drawbacks, e.g., poor performance on noisy data. Hence, further studies may need to carefully compare the results of multilevel regression and random forest models; relying on a single method may lead to misleading results.

4.2. Planning implications

We tentatively propose two design suggestions for the underground space based on the above analysis and findings.

First, we should carefully consider the distance between major destinations to railway or metro stations because public transport stations are significant pedestrian generators. This study showed that the average pedestrian flow, which was relatively high mainly distributed within 400 m from the Hongqiao Hub. Besner (2007) believes that the location of subway stations affects the distribution of pedestrian flow in the underground pedestrian space. For example, the Montreal underground pedestrian system has planned six subway stations in the core area. The distance between subway stations on the same line is about 400–500 m, and the distance between subway stations on different lines is about 700 m. Under these circumstances, the distribution of the pedestrian flow is relatively balanced. However, there is only one metro station in this underground space, and the farthest walking distance from the Hongqiao Hub to the destination is up to 1 km, which may exceed the norm and lead to reluctance to walk in the underground space.

Therefore, when planning the underground pedestrian network, the location of the stations should be considered. Related major construction projects should be located within about 500 m of the railway or metro stations, so that the pedestrian flow in the underground space can be evenly distributed. When the distance to the stations is too long, additional metro stations should be constructed. If it is impossible to add more metro stations, it is still feasible to add moving walkways and attractive places in some underground passage sections to make up for the long walking distance and low vitality in these spaces.

Second, from the perspective of the planning process of the Hongqiao hub (Xiong et al., 2020), various headquarters business and office functions were first introduced into the core area of the Hongqiao business district, and then supporting residential and public services were added to the periphery of the business district. Currently, the core area of Hongqiao Business District (Phase I) is dominated by commercial and office functions, with almost no residential function involved. The supply of urban supporting functions such as public facilities and public spaces is also seriously insufficient. In addition, the north side of the underground central axis is mainly office functions, which attracts many employees during weekdays but not weekends. These two reasons have led to a sharp decrease in weekend pedestrian flow on the north side of the underground central axis and an overall uneven distribution of spatial vitality.

Therefore, moderately mixing residential, apartment and hotel functions into this site and rationally allocating some commerce and office functions on both sides of the underground central axis should be better solutions. These solutions can change the user composition, increase pedestrian flow, and promote vitality in the core area of Hongqiao Business District in different time periods.

4.3. Limitations

There are several limitations. First, environmental factors, e.g., temperature, noise, humidity, and wind speed, may also influence people's willingness to walk in the underground space (Zacharias & Wang, 2021). However, these data were unavailable in this study and needed to be considered in further studies. Second, some parts of the underground space of the Hongqiao Transportation Hub have not yet been fully completed. The pedestrian flow may be redistributed when destinations are constructed. Thirdly, we only observed the pedestrian flow of this study area for two days. The long-term pedestrian flow patterns, such as seasonal fluctuation and the impact of changing weather on pedestrian flow, are worth exploring.

5. Conclusions

This study takes the underground space of Shanghai Hongqiao Business District (Phase I), one of the most successful integrated railway station-city development projects, as a case to explore the spatial and temporal distribution characteristics of spatial vitality and its influencing factors. Multilevel linear models were used to analyze the relationship between pedestrian flow and its influencing factors. Random forest models were used to investigate the relative importance of influencing factors on spatial vitality. The main conclusions are as follows.

1. The spatial vitality in this underground space was uneven on weekdays or weekends. The spatial distribution of pedestrian flow was relatively high among the three locations near the Hongqiao hub and relatively low in other places. Also, the pedestrian flow on the north side of the central axis passage was about 55% higher on weekdays than on weekends, while the pedestrian flow on the south side was about 25% higher. The temporal distribution of pedestrian flow indicates that people on weekdays are mainly for transferring and commuting, while people on weekends are mainly for shopping and leisure.
2. The distance to the transportation hub and the accessibility of the underground space (integration calculated by space syntax) are the two most essential factors for spatial vitality on both weekdays and weekends. The number of retail stores and walkway width were positively correlated with the spatial vitality only on weekends. The difference in influencing factors on weekdays and weekends indicates the different usage patterns in the underground space. The results of random forest models further verified the results of multilevel linear models.
3. To improve the spatial vitality of underground space, the location of the stations should be carefully considered. When the distance of destinations is far away from the stations, it is suggested to construct more metro stations or add moving walkways and attractive places in some underground passage sections. In addition, moderately mixing residential, apartment and hotel functions and rationally allocating some commerce and office functions on both sides of the underground central axis are recommended.

Overall, the results shed light on our understanding of the spatial vitality in the underground space and provide some tentative suggestions for the planning and design of underground space in high-density cities.

CRediT authorship contribution statement

Zhenhua Li: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Yi Lu:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Yu Zhuang:** Supervision, Writing – review & editing. **Linchuan Yang:** Writing – review & editing.

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.

Data availability

Data will be made available on request.

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