Underground space in metro area: constituent, influencing factors and improving strategies of the spatial vitality

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Abstract. Nowadays, the shortage of available urban land and the booming construction of urban subway are driving the rapid development of Underground Space in the Metro Area (USIMA) which is an important constituent in the compact development of cities. Spatial vitality, as one of the most important evaluation indicators for the layout of such metro-related underground space, is closely related to spatial efficiency. Therefore, taking Shanghai People's Square Metro Station (SPSMS) as a case study, this paper investigated the variable factors of the spatial vitality in USIMA by using methods of space syntax, field investigation, and pedestrian counting. Results revealed that the spatial vitality of USIMA is comprehensively affected by related variables, including accessibility and visibility of spatial configuration, degree of functional mixture, layout of station hall as well as entrances/exits, and the organization of business forms. Finally, improvement suggestions and discussions are put forward from the aspects of entrance/exit layout, spatial organization, and functional distribution, to provide reference for future planning, design and optimization of USIMA with effective vitality.

1. Introduction
Nowadays, the process of accelerating urban construction has brought about threats to the sustainable development of cities in terms of insufficient land and scarce urban space. Underground space is explored as an available compensated solution to alleviate the disequilibrium between the demand of space for booming development and the apparent lack of aboveground space. It has been pointed out that the exploitation of underground space expands the domestic demand of a city and centralizes its local development [1-3]. Currently, the concentrated development of local regions within cities is mainly based on rail transit stations [4, 5], which integrate people of certain region and the underground space to generate local activities [6, 7]. Rail transit stations guide or even control the structures and integral patterns of underground space and the surrounding regions, and more importantly inspire the vitality of a city [7]. Such underground space linked to the development of metro construction is collectively referred to as "Underground Space in the Metro Area (USIMA)", and its development receives increasing demands in recent years [7, 8]. Cheng[9] determined that USIMA has become an important component of the comprehensive exploitation of underground space in China, contributing to special effects to the promotion of city vitality and improvements of the ecological and traffic environments of a city. Peng[8] pointed out that USIMA is the junction between urban rail transit and functional zones of land utilization. The exploitation of USIMA not only provide effective and comfortable transfer for citizens, but also promote the space coordination and function optimization of surrounding zones as well as enhanced regional attraction for sustainable development.
At present, the development of urban rail transit construction in China is rapid in terms of both the speed and annual increment [11, 12]. In 2018, the number of cities with a metro system increased to 32, and the total length of the rail transit of China has reached 5065km, which ranks the first worldwide. Numerous underground space have been successfully developed based on rail transit stations, including Shenzhen Futian CBD, Wuhan Optics Valley Square, and Shanghai Hongqiao Business District, etc. Qian [6] pointed out that in the next 20 to 30 years, the development of USIMA in China will remain in a rapid mode with the vast construction of metro station.

Although many achievements have been gained in the construction of USIMA in China, there are still many problems to be solved [12, 13]. Currently, great attentions regarding on the theoretical research of USIMA have been paid on the aspects of construction technique, planning mode and environmental design [9, 13-15]. However, spatial vitality, the most important aspect of USIMA is seldom involved. This reflected in that parts of the developed USIMA are left unused or even abandoned due to the extremely low vitality [11, 15]. Therefore, methods of enhancing as well as predicting the spatial vitality of USIMA should be developed to achieve the high spatial efficiency.

2. Literature review

At present, studies on spatial vitality mainly focus on the topics of municipal streets and urban space [16-19]. Vitality of underground space, especially the vitality of USIMA has not been studied and reported. Therefore, in this research, we reviewed the traditional vitality research firstly, to find an available research method for USIMA vitality.

Table 1. The components of traditional urban spatial vitality

| Elements of urban spatial feature | Jane Jacobs [20] | Katz Peter [21] | Jan Gehl [22] | Roger Trancik [23] | Montgomery John [16] |
|----------------------------------|------------------|-----------------|---------------|-------------------|---------------------|
| Street-network configuration (accessibility and visibility) | Short streets; Intensity of pedestrians | Pedestrian friendly | To integrate not segregate; To assemble not disperse | Linking sequential movement; Axis and perspective; Integrated bridging | Fine grain; Human scale; Streets: contact, visibility, and horizontal grain; City blocks and permeability |
| Functional mixture | A mixture of primary use; A mixture of building ages | Mixed land use; Daily living in walk distance | Mixed land use; To integrate not segregate | Indoor/outdoor fusion | Mixed land use; Public realm |
| Building form | / | Compact; Appropriate building densities | To invite not repel; To open up not close in | Edge continuity | Development intensity; Human scale |
| Other features | / | Economic health and harmonious evolution; A range of parks | Slow traffic | / | Green space and water space; Landmarks, visual stimulations and attention to detail; Architectural style as image |
Based on the reinterpretation of the morphology of traditional urban spatial vitality, it's summarized that all of the related classical work on spatial vitality originate from the exploration of urban spatial characteristic. According to Jacobs[20], vibrant streets with high vitality have the attributes of short length, high pedestrian density, mixed function and building with multi ages. Katz et al. [21] believed that compactness, walking scale, mixed function, and proper density of buildings are important factors affecting vitality. Montgomery [16] pointed out that space with high vitality should have detailed texture, human scale, mixed function and connected streets. Jan[22] analyzed the influence of functional mixture, slow traffic, and open space on vitality. These researchers expound the constitution principle of the morphological features of spatial vitality from a qualitative perspective that, urban spatial vitality is defined as a city activity based on the influence of urban spatial characteristic. In other words, urban spatial vitality is the entirety of spatial feature and social activity. It should be defined from the aspects of spatial characteristic and citizens' activity intensity.

Additionally, most of the founding principles of spatial vitality can be summarized into three key elements of urban spatial characteristic which are: 1) well-established street network configuration with high accessibility and visibility, 2) proper architectural forms with appropriate building densities, architectural composition, and continuous edge, and 3) adequate functional mixture, as further presented in Table 1. Since the underground space is an enclosed architectural space, it is difficult to discuss USIMA with the element of "proper architectural form". Moreover, the applicability of other two elements, “well-established street-network configuration” and “adequate functional mixture” to USIMA are unclear. And whether there exist other elements influencing the spatial vitality of USIMA is unknown.

3. Research aims and research questions
Based on the above morphological interpretation of the spatial vitality of traditional cities, a hypothesis is proposed concerning on the construction of spatial vitality for USIMA. When USIMA has well-established spatial configuration with high accessibility, visibility, as well as adequate functional mixture, its spatial vitality can be effectively constructed. To this end, the spatial morphological characteristic of USIMA and social activity will be quantitatively analyzed respectively, subsequently compared to verify the hypothesis, then factors affecting spatial vitality of USIMA can be investigated. Additionally, two problems need to be solved: a) how to elaborate the spatial morphological characteristic of USIMA quantitatively; and b) how to measure social activity quantitatively. Finally, the objectives of this research could then be defined using the following two research questions: 1) Will the spatial morphological characteristics, including the appropriate spatial configuration and adequate functional mixture, affect the spatial vitality of USIMA? 2) Are there other elements that affect the spatial vitality of USIMA?

4. Methodology
To answer the above questions, the underground space of Shanghai People's Square Metro Station (SPSMS) was selected as the research sample in this study. Three rail transit lines, No. 1, No. 2 and No. 8 converge in this station which also embraces several urban complexes. The spatial scope for analysis is the public walking space on the basement one floor, and the surrounding underground shopping malls were not included. Specific research methods are as follows:

4.1 Space syntax
Space syntax was co-created by Bill Hillier, Julienne Hanson, et al in the 1970s[24]. It is one of the newly developed quantitative research methods in urban morphology, which studies space as an independent element, and analyzes the relationship between space and architecture, society, cognition and other fields through mathematical calculation [25, 26]. In this paper, axial analysis and visibility analysis were included to explore the spatial structure of the SPSMS.
4.2 Pedestrian counting
Pedestrian counting was used to obtain the actual population density during field investigation. Since the SPSMS locates in the central business district, it has great spatial attractions and traffic potential, with characteristics of large human flow, wide-ranging activity, long-path tracking and diversified destinations. Therefore, manual counting is adopted to record the pedestrian volume of each entrance/exit and selected nodes in the underground space during a specific time period. Furthermore, the intensity of activity can be indirectly examined and used as an indicator to measure the spatial vitality.

5. Spatial features of SPSMS
The spatial features of the SPSMS will be studied in this section to explore the variable factors of spatial vitality in USIMA. Since the station hall (payment area) has a relatively stable passenger flow, the connection space that the non-paid area of this station is the research priority. To facilitate the analysis, the research area is divided into 10 regions as illustrated in Figure 1.

![Figure 1. Partition diagram of SPSMS](image1)

![Figure 2. The axial map analysis of integration and connectivity.](image2)
5.1 Analysis of spatial configuration

5.1.1 Accessibility analysis. Accessibility of the SPSMS is firstly discussed by mean of axial analysis to reveal the spatial configuration. Four quantitative indexes: integration degree ($r=3$), mean depth value, choice value and connectivity value of space are calculated, as illustrated in Figure 2 and Table 2. In Figure 2a, the red axis with the highest degree of spatial integration is distributed in the station hall, which locates in the centre of the transfer hall. High integration axes are connected to each other, extending from the station hall to the southeast until exit No. 1, running through B4 and C1 region. This constitutes the core region of integration degree with great accessibility in the overall space. While, the corridor spaces in C2, D1, and D2 region are spatially very isolated (the blue part of the lower right corner in Figure 2a), with an average integration degree of 2.74, which is far lower than the average value of the whole space (Table 2). Moreover, the analysis results of connectivity value are consistent with the index of integration degree (Figure 2b), which will be compared with the field survey in the following contents.

Table 2. Descriptive statistics of the spatial attributes values for SPSMS.

| Region | Integration | Mean Depth | Choice | Connectivity |
|--------|-------------|------------|--------|--------------|
| Average value |            |            |        |              |
| A 1    | 3.44721     | 2.61191    | 305.6  | 14.5625      |
| B1     | 6.71695     | 2.0233     | 839.861| 93.8333      |
| B2     | 5.97541     | 2.04214    | 598.667| 47.333       |
| B3     | 6.47803     | 2.0716     | 545.568| 77.7692      |
| B4     | 7.69746     | 1.82266    | 420    | 93.2059      |
| C1     | 10.5018     | 1.58434    | 2859   | 183          |
| C2     | 2.75149     | 2.94455    | 60     | 2.5          |
| D1     | 2.60804     | 2.9533     | 12     | 3            |
| D2     | 2.86817     | 2.62572    | 190    | 3.5          |
| E1     | 8.18038     | 1.7655     | 749.473| 130.573      |

Figure 3 presents the axial map analysis of mean depth value and choice value to further reveal the spatial accessibility. As can be found in Figure 3a, the mean depth value has an opposite trend to the
integration degree; the topological depth of regions with high integration degree is low. Table 2 identifies that the average value of topology depth in C1 region is only 1.58 with the best accessibility. On the contrast, D1 region has the worst accessibility as its topological depth value is as high as 2.95. In addition, as can be seen from the quantitative calculation results of choice value shown in Figure 3b, the connection space with the highest choice value is C1 region and north side of the B1 region in sequence. The choice value is significantly higher than that of other regions in the space, in which C1 region is as high as 2859, and the possibility of the space being traversed is the largest.

Based on the above analysis of the four syntactic variables, the connection space is classified into 5 grades which are: extremely high accessibility (region C1), high accessibility (regions B1 and B4), medium accessibility (regions B2 and B3), poor accessibility (region A1) and extremely poor accessibility (regions D1, D2 and C2).

5.1.2 Visibility analysis. To further explore the spatial configuration of SPSMS, visibility analysis is carried out by calculate two quantitative indexes of visual integration degree (r=3) and visual mean depth value of space. As shown in Figure. 4a, the area with the highest visual integration degree is located in the transfer hall. The whole area of the hall displays a warm yellow tone with best visibility, which is suitable for the layout of public space. In addition, for connection spaces, the area with the highest visual accessibility is B1 region, followed by C1, B4 and B3 region, with better visibility and high-potential activities. Visual integration degree of other spaces decreases successively from the centre to the surrounding area. Hong Kong famous street in D2 region has the weakest visibility, of which the average is just 2.58. It's followed by D1 region, C2 region and A1 region. Moreover, the visual mean depth is opposite to the visual integration degree, which is consistent with the above analysis of visibility (Figure. 4b).

Figure 4. Visibility analyses.
Table 3. Grade of spatial configuration

| Grade | Index | Accessibility | Visibility | Reasonable degree of spatial configuration |
|-------|-------|---------------|------------|------------------------------------------|
| I     | C1    | B1            | C1,B1      |                                          |
| II    | B1,B4 | C1,B3,B4      | B3, B4     |                                          |
| III   | B2,B3 | B2            | B2         |                                          |
| VI    | A1    | A1            | A1         |                                          |
| V     | D1,D2,C2 | D1,D2,C2  | D1,D2,C2  |                                          |

Note: from grade I to grade V representative index from high to low

Considering the results of accessibility and visibility, we divided the spatial configuration of the underground connection space of SPSMS into 5 levels. Theoretically, the better the spatial configuration, the easier the crowd could gather, and the higher the spatial vitality of space is. As shown in Table 3, C1 and B1 regions have the best spatial configuration, which are the spaces with most pedestrians. C2, D1, and D2 regions have extremely low visibility and accessibility, which are spaces with weak spatial vitality potentially and are unsuitable for commercial layout.

5.2. Investigation of functional mixture
This section will further analyze the spatial characteristic of SPSMS from the perspective of spatial function. In respect of the special location of USIMA, the analysis includes two aspects: the internal function of underground space and the external urban function.

5.2.1 Internal spatial function. Field investigation was carried out on the functional layout and format combination of the research area. As shown in Figure 5, it can be seen that the central region of SPSMS is primarily used for transportation transfers, while the commercial area is in the peripheral spaces. Furthermore, most regions of the SPSMS are presented with single functions, only the Washington pedestrian street in region A1and B1 has multiple functions, like evacuation, shopping, and catering. In addition, rail transit, as a special function for USIMA, has a strong ability to attract population, and the area adjacent to the station hall has the condition of vitality enhancement.

5.2.2 External urban function. The corresponding external city functions of each region were analyzed to further understand the hidden spatial function of SPSMS. As the exit is the only passage between the underground space and the urban surface, when the external urban function has an impact on the vitality of each area, it will be reflected by the pedestrian's choice of exit. Thus, the vitality of these areas adjacent to exits can be accordingly improved. According to the exit survey results, the regions connecting to six exits with large passenger flows (3000-5000p/h) are region A1 (connecting to No. 10), region B3 (connecting to No. 19, No. 14 ad No. 15) and region C1 (connecting to No. 1).

6. Social activity
Section 5.1 and section 5.2 make a specific analysis of the spatial characteristic of SPSMS. In this section, pedestrian flow was measured to further study the distribution characteristics of spatial vitality and influencing factors of USIMA. 15 nodes in the connection space of SPSMS were selected to collect the pedestrian flow through manual counting (Figure 6), and data was recorded every five min during 7:00 am to 12:00 am. Finally, the average pedestrian flows of each node in SPSMS are obtained through comprehensive calculation.
The result is shown in the Figure 7. It can be seen that the overall fluctuation trend of most nodes is generally similar. During 7:00-9:00am, there is a relatively significant increase in passenger flow, which reaches the top between 8:20-8:40am. The differences of passenger flow in B3 region (node 7 and 9), B4 region (node 8) and A1 region (node 1, 2 and 4) are intuitive. Moreover, as can be seen from Figure 7, regions with the highest pedestrian flows are B1 region, B3 region and B4 region, suggesting strong spatial vitality. Nevertheless, region C2 (node 11), D1 (node 14) and D2 (node 13 and 15) have much low passenger flows, indicating weak space vitality.
7. Discussions
To verify the rationality of the analysis results and the effects of related factors on spatial vitality (V), a model of multiple linear regression (MLR) was developed to discuss the factors relevance of spatial configuration (C), rail traffic (R), entrances/exits (E) and functional mixture (F), which is expressed in Eq. 6,

\[ V = a_0 + a_1 C + a_2 R + a_3 F + a_4 E \]  

where \( a_0 \) is a constant, \( a_i (i=1, 2, 3, 4) \) is the regression coefficient of independent variable.

Based on the analysis of MLR by SPSS, the results are that \( r^2 = 0.966 \), the test value of F equals to 70.997 and the coefficients of significance of p are both less than 0.05. This suggests that the analysis model has statistical significance, as presented in Table 4. It thus can be found that the spatial vitality of USIMA is affected by the spatial configuration of space, rail transit station, degree of the function mixture and layout of entrance/exits synthetically. In addition, the Pearson's correlation coefficient of local integration and rail transit station reach 0.892 and 0.772 respectively, displaying very high correlation. The final analysis model of MLR is thus expressed in Eq. 7,

\[ V = 3.779C + 4.891R + 2.540F + 2.043E - 11.989 \]  

Table 4. Inspection result of multiple linear regression

| Variable     | Constant | C  | R  | F  | E                  |
|--------------|----------|----|----|----|--------------------|
| Pearson Correlation | -11.989  | 0.892 | 0.772 | 0.575 | 0.632               |
| Sig.         | 0.000    | 0.000 | 0.000 | 0.012 | 0.006              |

8. Conclusions
This paper took the SPSMS as the case study to explore the influence factors of spatial vitality of USIMA through quantitative analysing the spatial characteristic and pedestrian volume of the SPSMS. It is proved that the spatial vitality of USIMA is under the comprehensive influence of multiple factors such as: the visibility and accessibility of spatial configuration, the involvement of rail transit, the degree of functional mixture (internal format layout), the layout of entrances/exits (external urban functions) and the organization of business forms. Moreover, the feasibility of spatial characteristic analysis method for the prediction of spatial vitality of USIMA was also verified. Finally, corresponding suggestions and discussions on the optimization of USIMA planning in the future are put forward from the three aspects of layout of entrances/exits, design of spatial configuration, and functional layout.

First, for the layout of entrances/exits of USIMA, a great attention should be paid to its relationship with the ground urban space to match the demand with the passenger flow of the station. Second, in the initial stage of design, space syntax can be used to predict and analyze the rationality of space structure, including accessibility, visibility, intelligibility and synergy. And take this as a reference to optimize the design scheme. Third, as the distribution of rail transit and exits are closely related to the vitality of underground space, it is necessary to ensure the rational utilization of the functional advantages of rail transit and exits (external cities) to stimulate the activities of citizens and enhance the vitality of space.

Finally, since Complexity of spatial features and the limited manpower, the research process and results have certain limitations, but it also provides an insight into the future in-depth study of the planning and design of USIMA.

Reference:
[1] Peng FL, Qiao YK, Zhao JW, Liu K, Li JC 2019 Tunn. Undergr. Space Technol. 95 103176.
[2] Qiao YK, Peng FL, Sabri S, Rajabifard A 2019 Sust. Cities Soc. 51 101757.
[3] von der Tann, Sterling R, Zhou Y, Metje N 2020 Undergr. Space 5 144-166.
[4] Demers C 2016 Procedia Eng. 165 726-729.
[5] Wang J and Go A 2018 Sichuan Architecture 38 113-19. (in Chinese)
[6] Qian Q H 2016 Tunn. Undergr. Space Technol. 55 280-289.
[7] Chen X 2018 Jiangsu Construction 5 1-5. (in Chinese)
[8] Peng J, Peng FL, Yabuki N, Fukuda T 2019 Tunn. Undergr. Space Technol. 91 103009.
[9] Chen X 2015 Engineering practice and innovation of underground space utilization in metro area (Beijing: People's traffic).
[10] Chen ZL, Chen JY, Liu H, Zhang ZF 2018 Tunn. Undergr. Space Technol. 71 253-270.
[11] Zhao JW, Peng FL, Wang TQ, Zhang XY, Jiang BN 2016 Tunn. Undergr. Space Technol. 55 290-307.
[12] Bartel S and Janssen G 2016 Tunn. Undergr. Space Technol. 55 112-117.
[13] Yuan H, He Y, Wu Y 2019 Sust. Cities Soc. 48 101541.
[14] Delmastro C, Lavagno E, Schranz L 2016 Tunn. Undergr. Space Technol. 55 103-111.
[15] Li X, Xu H, Li C, Sun L, Wang R 2016 Tunn. Undergr. Space Technol. 55 52-58.
[16] Montgomery J 1998 J. Urban Des. 3 93-116.
[17] Ye Y, Zhuang Y, Zhang L 2016 Int. Urban Plan 31 26-33.
[18] Zeng C, Song Y, He Q, Shen F 2018 Sust. Cities Soc. 40 296-306.
[19] Lan F, Gong X, Da H, Wen H 2019 Cities 100 102454.
[20] Jacobs J 1992 The Death and Life of Great American Cities. Vintage.
[21] Katz P 1994 The New Urbanism: Toward an Architecture of Community. McGraw-Hill.
[22] Jan G 1987 Life Between Buildings. Van Nostrand Reinhold.
[23] Roger T 1986 Finding lost space. Van Nostrand Reinhold.
[24] Hillier B 2007 J. Urban Des. 3 333–335.
[25] Giannopoulou M, Roukounis Y, Stefanis V 2012 Procedia Soc. Behav. 48 1887-1896.
[26] Xia C, Yeh AG, Zhang A 2020 Landsc. Urban Plan. 193 103669.

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