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ORIGINAL ARTICLE

A Study of Walking Perceptions in Large Underground Parking Lots

Yuan Ying[1], Peng Jun Nan[1], Li Hui[1], Huang Zong Cai[1], Ye Lian Hong[1]

Institute of Spatial Information Technology, Xiamen University of Technology, Xiamen, Fujian, 361024, China)

***Corresponding Author: Yuan Ying**

Abstract

With the acceleration of urbanization and the popularity of cars and other means of travel, underground parking lots have become a key node site for switching from driving to walking for mass travel. Due to the closed space, complex terrain and large number of parking lots, pedestrians in underground parking lots will face challenges such as unclear direction and difficult to find entrances and exits. To address this situation, taking the underground parking lot of a large shopping center as an example, based on spatial syntax and other theories, we calculate the convex spatial integration degree, visual integration degree, and walking distance and other indicators to comprehensively assess the walking perception of the underground parking lot, and then analyze the walking perception of pedestrians in each area of the underground parking lot and the change of the walking perception under different parking rates. The results show that: (1) The average value of the overall walking perception of the underground parking lot is low, only 0.41, indicating that pedestrians have difficulties in locating entrances and exits. (2) With the increase of parking rate, the global average walking perception of underground parking lot decreases significantly from 0.41 to 0.25, which indicates that the increase of vehicles leads to the deterioration of pedestrians' walking experience, especially in the case of high parking rate, which makes it difficult for pedestrians to locate entrances and exits. The results of the study can provide practical references for the pedestrian planning of underground parking lots, the spatial layout and optimization of guide signs, and provide a basis for the development of effective strategies to improve the access efficiency and user experience of underground parking lots.

Keywords: **Walking Perception; Underground Parking Lot; Spatial Syntax; Integration Degree**

Introduction

With the rapid acceleration of urbanization, large and even very large buildings are continuously being completed and put into use. These buildings are often equipped with expansive underground parking lots to meet the growing demand for urban parking. Such underground parking facilities are becoming key transition points for the public, where the shift from driving to walking occurs. However, due to the confined space, complex layouts, and large number of parking spaces, pedestrians often face challenges such as unclear directions and difficulty locating entrances and exits, which negatively impacts the overall travel experience. To address these issues, the main factors influencing wayfinding difficulties in underground parking lots are explored, focusing on the spatial structure of these large facilities.

With the rapid construction of mega-buildings in major cities and the continuous increase in the number of transportation means, research on underground parking lots has been carried out both at home and abroad. Foreign research focuses mainly on the management of underground parking lots and vehicle positioning problems. Among them, Yuanqi Zhang utilizes LoRa wireless communication technology to realize parking space control and detection information collection, automatic payment and automated parking management to improve the efficiency of parking lot management[1]; Zhuoyi Jiang utilizes a multi-scale localization method to achieve highly accurate vehicle positioning by constructing multi-layer maps using only a monocular camera[2]; Beomju Shin proposed a novel navigation system for underground parking lots that utilizes Long Term Evolution (LTE) signals for vehicle localization, which estimates the location of a vehicle by summing up the LTE signal strength and comparing it to a pre-stored database of LTE received signal strength (RSS) [3].

In China, more attention has been paid to the problems of “difficult to park, difficult to find a car” and parking lot management [4,5]. Shu Zhang obtains community camera data in real time through a multimodal data fusion framework, processes and fuses the scene data efficiently, and realizes the function of visual display of empty parking spaces and real-life parking space guidance in parking lots [6]; Zhongsheng Tan integrates static and dynamic urban traffic, guides the regional traffic flow, optimizes the urban layout, and increases the utilization rate of parking lots, and creates intelligent parking management system by using the Internet and the Internet of Things (IoT) technology. management system, including features such as intelligent reservation, vehicle guidance and intelligent identification, in order to achieve effective management and safety protection of parking lots [7].

Although scholars at home and abroad have done a lot of research on the problems related to underground parking lots, there are relatively few studies on the spatial perception of pedestrians in underground parking lots, and the industry has not yet formed a unified standard to measure the difficulty of pedestrian wayfinding in underground spaces. In the field of underground rail transportation, Wang Linjie proposed the concept of pedestrian perception to measure the perception and wayfinding ability of pedestrians in confined spaces, which provides a research framework for the difficulty of pedestrian wayfinding in underground spaces [8]. Walking Perceptibility is based on the spatial syntax [9-13], which comprehensively evaluates the walking perceptibility of the study area through the topological connectivity of each part of the space, the access relationship between the parts and the walking distance, and measures the pedestrians' location perception and wayfinding ability in a large-scale confined space. This study expands on the research framework of walking perception, and adopts the entropy weighting method to assign weights to the relevant indicators of walking perception in specific places such as underground parking lots, and determines the importance of each indicator through the distribution characteristics of the data, so as to minimize the influence of subjective judgments on the weights.

Because of the complex layout and closed space inside the underground parking lot, the visibility is changing under the influence of different parking rates. This thesis further studies the change of walking perception in each area under different parking rates, and finds out the areas where walking perception is always lower; and takes these areas as the key optimization areas of pedestrian walking guidance system in underground parking lots, which provides reference for the construction of pedestrian walking guidance system in underground parking lots.

1 Study Area and Data Sources

1.1 Study Area

The study area is located in the negative 3 levels of the basement of a shopping mall in Xiamen City. It has a total area of 31,844 square meters and contains 544 parking spaces. The parking spaces are arranged at right angles, with appropriate spacing between neighboring parking spaces to ensure the convenience of vehicle access and pedestrian movement. The width of the driving lane reaches 7 meters, providing sufficient space for vehicles to move smoothly. As shown in Figure 1, the blue area is for parking spaces and the white area is for equipment rooms and walls. In addition, there are three pedestrian entrances to the underground parking lot, labeled Entrance 1, Entrance 2, and Entrance 3.

Figure 1 Study area

1.2 Data sources

The data for the study area was obtained from CAD drawings of the architectural design of a shopping mall in Xiamen City. The study data is in DWG format and contains information on the layout of the underground parking lot, the floor area, the overall floor height, and the total number of parking spaces.

2 Research Methodology

2.1 Walking Perception Evaluation Method

Walking perception refers to the degree of perception and experience of pedestrians for their surroundings, including pedestrians' perception and evaluation of the accessibility, visibility and convenience of the walking environment, which measures the degree of pedestrians' perception and understanding of their surroundings when walking, and reflects the ease with which they can arrive at their destination from their current location. In this paper, three elements of walking space accessibility, visibility and walking distance are selected as the evaluation indexes of walking perception in underground parking lots.

For the above three evaluation indicators, this study uses spatial syntax theory to quantify spatial accessibility, visibility, and walking distance as convex spatial integration, visual integration, and walking distance, respectively.

(1)Convex spatial integration: In spatial syntax, convex spatial integration refers to the degree to which a space is connected and interrelated with the surrounding spaces [14,15]. A high degree of convex spatial integration indicates that its local space is more closely connected to the overall spatial system, and the walker can more clearly perceive where he/she is and the relationship with the destination. The value is the average of the shortest distance between a convex space and other convex spaces in the whole, the larger the value, the higher the accessibility of the space in the overall space. As shown in equation (1).

$$I_i = \frac{n\left[\frac{log\,2(n+2)}{3}\right]+1}{(n-1)(MD-1)} \quad (1)$$

$$MD = \frac{\sum_{j=1,j\neq i}^{n} D_i^j}{n-1} \quad (2)$$

Where: I_i refers to the integration degree of the ith space; MD refers to the value of the average depth of the ith space ,i.e., the minimum number of connections that the space needs to pass through in order to reach the other spaces [16];D_i^j is the minimum number of connections that the space i needs to pass through in order to get to the space j; and n refers to the total number of spaces.

Table 1 Changes in the weights of each index under different parking rates

entropy weighting	0%	20%	40%	60%	80%	100%
Weighting of convex spatial integration	0.44	0.44	0.42	0.34	0.19	0.15
Visual Integration Weighting	0.36	0.35	0.38	0.5	0.72	0.78
Walking distance weights	0.2	0.21	0.2	0.16	0.09	0.07

(2)Degree of Visual Integration: In spatial syntax, the degree of visual integration refers to the degree of visual connection between the various elements of a space (e.g., rooms, roads, parking spaces, etc.) and between them and the overall environment, which is determined by a variety of factors such as layout, interrelationships, connectivity, and so on, between the elements. A higher degree of visual integration indicates that the element requires fewer turns to see the whole system and is easier to attract the eye. On the contrary, the more difficult it is to attract the eye. The formula for calculating its value is shown in (3) :

$$VI_i = \sum_j V_i^j \times D_i^j \quad (3)$$

Where: VI_i s the visual integration degree of the ith space; V_i^j is the visual visibility weight between space i and j, which is usually determined according to the visual angle between the two spaces, line-of-sight occlusion and other factors; D_i^j is the visual depth between space i and j, i.e., the number of visual transitions required to reach space j from space i.

(3)Walking distance: Walking distance can affect the pedestrian's walking perception. If the walking distance is long, the probability that pedestrians think they are not walking on the correct route will be elevated, thus reducing the walking perception. In this study, pedestrian entrances and exits are taken as destinations, and by calculating the average shortest walking distance from each convex space to all entrances and exits, the global average walking distance $\overline{D_\iota}$ in the entire underground parking lot can be obtained to evaluate the effect of walking distance on pedestrian walking perception. The calculation formula is shown below:

$$\overline{D_\iota} = \frac{\sum_j^n d_i^j}{m} \quad (4)$$

Where: $\overline{D_\iota}$ refers to the average walking distance of the ith space;d_i^j refers to the walking distance between the ith space and the jth entrance/exit; m refers to the number of entrances/exits in the underground parking lot; n refers to the total number of spaces.

In order to obtain a comparable walking perception index, the three evaluation index values are normalized, and their value ranges are mapped to between [0,1], and then the entropy weight method is used to determine the weight of each index based on the principle of information entropy according to the importance of each factor in walking perception, as shown in Table 1. Finally, through the weighted summation, a numerical indicator that comprehensively reflects the walking perception degree is obtained P. The calculation formula is shown below:

$$P = wI * NI_i + wV * NV_i + wD * ND_i \quad (5)$$

where wI, wV, and wD are the weighting factors of convex spatial integration, visual integration, and walking distance, and NI, NV, and ND are the normalized values of convex spatial integration, visual integration, and walking distance.

2.2 Data Processing and Calculations

(1) Convex space integration calculation: the parking lot is divided into convex spaces based on accessibility, and the parking spaces that can be reached in a straight line from the observation point without bypassing other spatial elements (e.g., walls and obstacles) are divided into one space, such as the blue part of Figure 2; other functional areas, such as the weak electricity room and the vehicle access channel, are each divided into an independent convex space, and the final result is shown in Figure 3, with a total of 125 convex spaces. After completing the division of convex spaces, the Graph Analysis function of the depthMap software is used to analyze the integration degree of the space in order to assess the connectivity of the space.

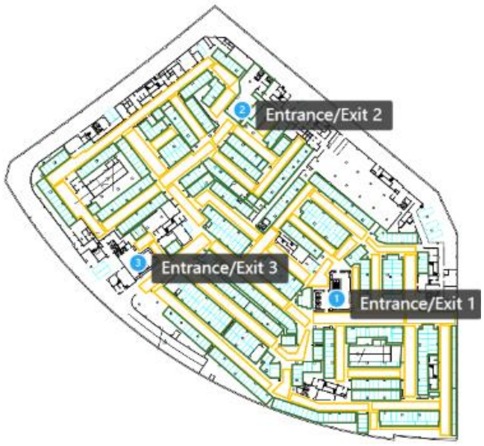


Figure2 Convex space division process diagram

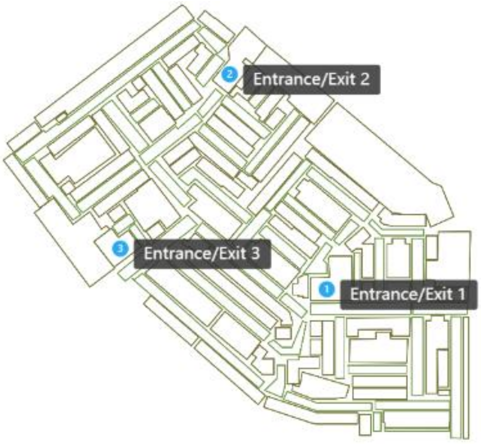


Figure 3 Convex space division result

(2) Calculation of Visual Integration Degree: Identify and mark the obstacles in the parking lot, such as columns and walls, and draw the spatial distribution map of these obstacles by using CAD software, and represent the obstacles as invisible areas in the model, as shown in the green part of Figure 4. Visual integration was calculated using the Visibility Graph Analysis function of the depthMap software to assess the visual accessibility and visibility within the parking lot, and the results are shown in Figure 5. Later, the spatially continuous visual integration degree is mapped to the delineated convex space by the method of calculating the average of all the visual integration degree grids in the convex space for unified analysis.

Figure 4 Viewshed model

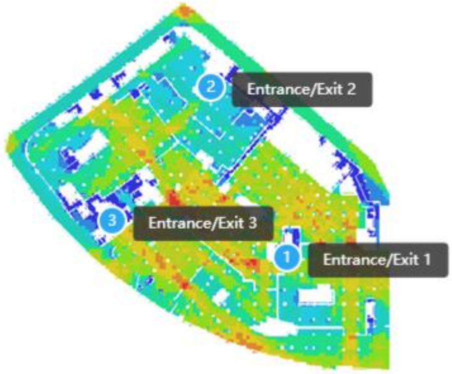


Figure 5 Visual integration

(3) Calculation of walking distance: Determine the center of mass of each convex space, take it as the reference point, measure and record the straight-line distance between adjacent convex spaces, and form a convex space walking network model. Calculate the shortest path from the center of gravity of each convex space to the entrance and exit of the parking lot, calculate the average length of all paths, and derive the average value of walking distance.

(4) Calculation of walking perception: the three factors of convex spatial integration, visual integration and walking distance average are normalized to eliminate the influence of the scale between different indicators. And according to the normalized data and the corresponding weighting factors, the final value of walking perception is calculated.

(5) Calculation of walking perceptibility under different parking rates: as the parking rate keeps increasing, resulting in an increase in the occupancy scale of parking spaces, the visual field model is greatly affected. First, we establish the baseline model of walking perception under 0 parking rate, when all parking spaces are idle. On this basis, the parking rate is gradually increased, and the view domain model is adjusted by simulating the scenario in which parking spaces are occupied, as shown in Figure 6. Assuming that the convex spatial integration and walking distance remain unchanged in this process, the walking perceptions under different parking rates are obtained by replacing the visual integration parameter in the visual domain model.

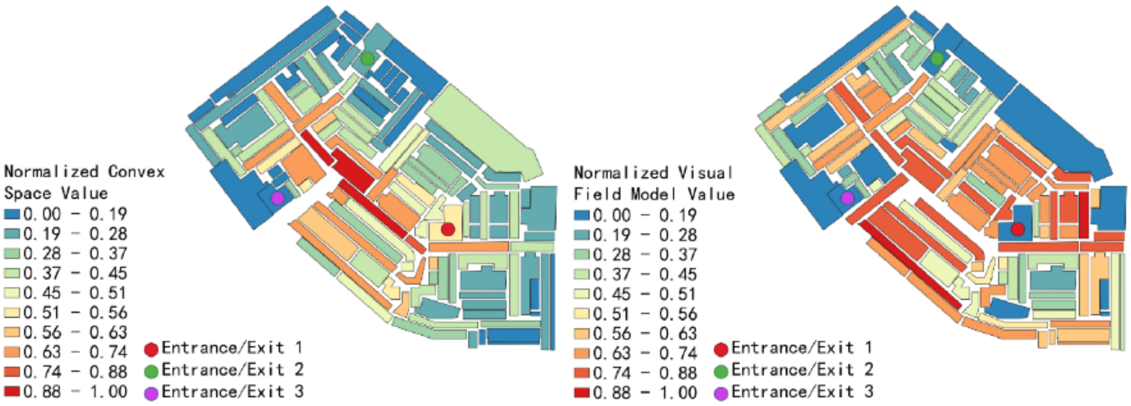
Figure 6 Viewshed models with different parking rates

3 Results and analysis

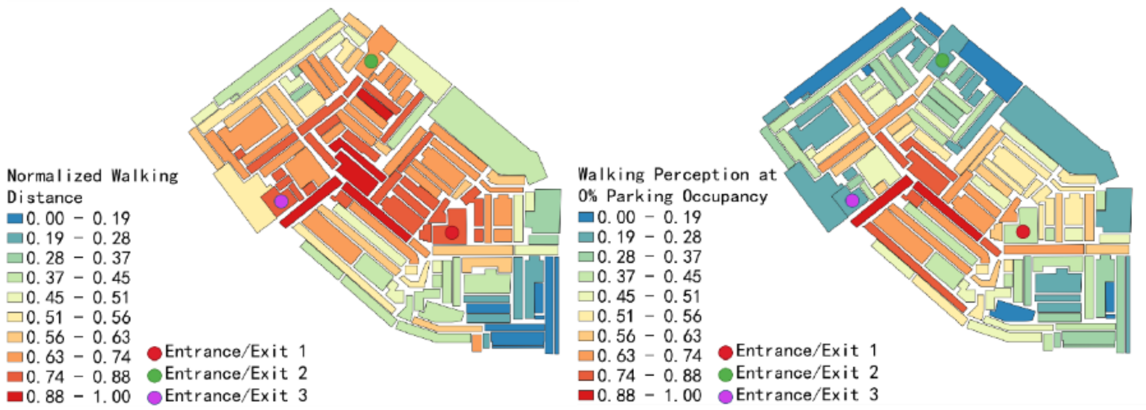
3.1 Visualization and Analysis of Walking Perceptions in Underground Parking Lots

The visualization tool of ARCGIS is used to visualize the level of walking perception. As shown in Figure 7(a). Locally, the convex spatial integration and visual integration of the center area are relatively high, while the walking distance is shorter, which leads to higher walking perceptions close to the center area, as shown in Figure 7(b), (c), and (d)

However, in the lower right area of the entrance/exit 1, the overall space has a relatively long walking distance, resulting in low perceptibility, a factor that significantly affects the walking perception, making it relatively low. In the peripheral area, there is some obscuring influence between the equipment surrounding it, which significantly reduces visibility, thereby affecting walking perception and making it more difficult to find the entrance/exit. Therefore, to ensure that pedestrians find and recognize entrances and exits more efficiently, special attention needs to be paid, especially in the proximity of entrance/exit 1 and in the peripheral areas.



(a) Normalized Convex Space Integration Value **(b) Normalized Visual Integration Value**



(c) Normalized Walking Distance Value **(d) Walking Perception**

Figure 7 Analysis of each factor

Parking lot access areas (e.g., the long striped area in the figure) have a relatively high level of pedestrian perception throughout the parking lot. These aisles typically provide good capacity and accessibility for vehicles to enter and exit parking spaces. At the same time, the width, lighting, and signage of the aisles make these areas more clearly perceivable to walkers. In contrast, areas around parking spaces tend to have more obstructions and sight obstructions due to the presence of vehicles and walls, which make these areas less perceptible to walkers.

As a whole, the walking perception of the underground parking lot decreases from the center to the periphery, and the pedestrians' ability to perceive the surrounding space gradually decreases. By further calculating the values in Figure 7(a), it can be seen that the average value of walking perception of this underground parking lot is 0.41, which indicates that it is relatively difficult for pedestrians to perceive the overall space and find the entrances and exits.

3.2 Evaluative Impact of Different Parking Rates on Walking Perceptions

Parking rates are included as one of the influencing factors for the parking function of underground parking lots. The parking rate reflects the parking situation of vehicles in the parking lot, which directly affects the walking path and perceived experience of walkers. As the parking rate increases, the number of occupied parking spaces increases, the walking space is compressed, spatial visibility decreases, and the walker's range of motion is limited.

In order to deeply investigate the effect of different parking rates on walking perceptions, different parking rate scenarios are set up, and parking rates of 0%, 20%, 40%, 60%, 80%, and 100% are taken as examples, and the changes of walking perceptions are observed in these scenarios in order to analyze the effect of different parking rates on walking perceptions. When examining the effect of parking rate on walking perceptions in underground parking lots, it is found that the global average walking perceptions show a decreasing trend as the parking rate increases. This is shown in Figure 8.

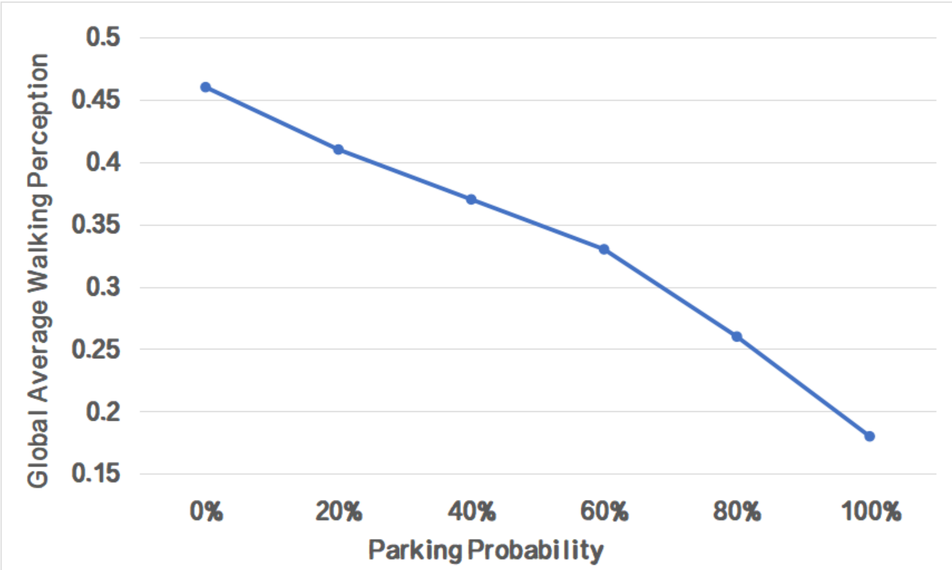
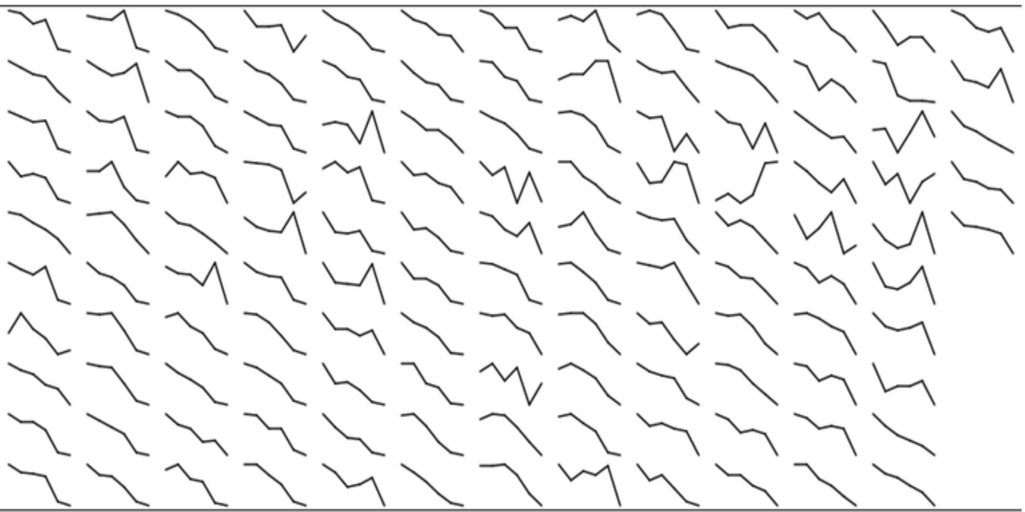


Figure 8 Changes in global average walking perception

Further, the walk perception of each specific area also changes accordingly with the change of parking rate. It was found that the walk perception in most areas of the underground parking lot was more sensitive to changes in the parking rate, and the walk perception in most convex spaces decreased significantly as the parking rate increased, as shown in Table 2.

Table 2 The trend of walking perception with the increase of parking rate in different convex spaces

Convex Space	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99	100-109	110-119	120-124
The Trend of Changes in Walking Perception at Different Parking Occupancy Rates													

In the case of a gradual increase in parking rate and a gradual decrease in visibility, the walking perception in the central area of the parking lot shows a gradual decrease. The increase in parking rate means that more parking spaces are occupied by vehicles, and the visual perception of space by pedestrians is weakened, which restricts and interferes with people's walking paths in the parking lot, thus decreasing the walking perception. The change in walking perception in the outer areas is not significant, and there are individual spaces where walking perception increases. As the parking rate gradually increases, the visual integration of the center area gradually decreases, resulting in difficulty for walkers to quickly acquire information about their surroundings. On the other hand, the peripheral area, which is less affected by the parking rate due to relatively fewer parking spaces, has a relatively higher degree of visual integration, and the walkers can perceive the surrounding environment and paths more clearly. The results are shown in Figure 9.

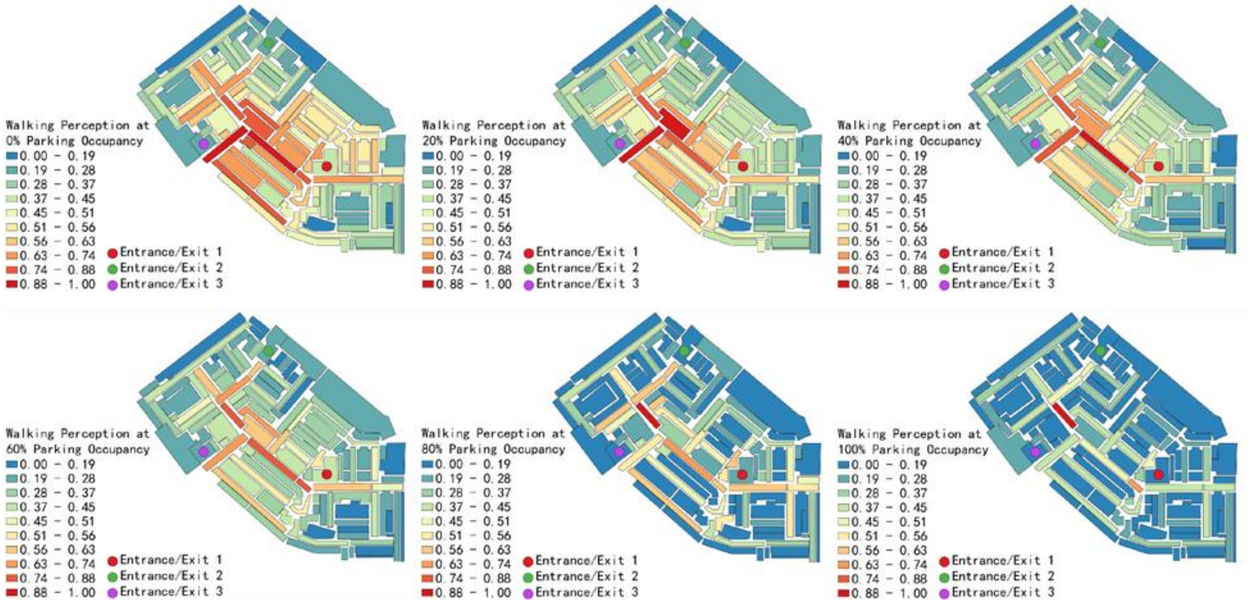


Figure 9 Changes in local walking perception under different parking rates

In addition, there are areas in underground parking lots where walking perception is consistently low. In order to enhance the walking perceptibility of these areas, measures such as installing additional markers, improving the brightness of lighting, and optimizing the spatial layout can be considered to enhance the perceptibility of pedestrians.

In the process of determining the evaluation index of walking perception, the authors of the paper carried out a site visit to verify the views of this paper through the on-site feelings of pedestrians. The results of the inspection show that in underground parking lots, the efficiency of pedestrians looking for entrances and exits is indeed affected by factors such as spatial layout accessibility, visual field, walking distance and accessibility, and the distribution of the degree of influence is basically in line with the calculation results of this paper.

Conclusion / Discussion

Aiming at the problems of pedestrian disorientation and safety hazards caused by the complex terrain and closed space of large underground parking lots, this study conducts an empirical study in a large underground parking lot, and uses the spatial sentence method and other methods to study the distribution characteristics of pedestrian perception from the perspective of pedestrian walking perception; and explores the spatial distribution and change trends of walking perception with the increasing parking rate.

The study shows that the spatial distribution pattern of walking perception in the underground parking lot shows a decreasing trend from the center to the periphery. This phenomenon reveals the importance of spatial layout for pedestrian walking experience: the center area is easy for pedestrians to locate and perceive the surrounding space due to its high connectivity, while the peripheral area is weaker in walking perception due to lower connectivity.

The peripheral areas are less connected, resulting in a weaker perception of walking. In addition, the spatial distribution pattern of walking perception changes under different parking rates. As the parking rate increases, the global average walkability of the underground parking lot decreases. When the number of vehicles is high, the occupancy of parking spaces can obstruct pedestrians' sightlines and travel routes, further affecting the walking experience. Based on these findings, the following recommendations can be provided to guide the design and management of underground parking lots:

1) For parking lots before construction, the method of this study can be applied to simulate and evaluate the spatial layout of the parking lot. By simulating different design options, the distribution of pedestrian walking perception is predicted, and design options with lower overall walking perception are screened out, so as to find the most optimal layout solution to enhance the spatial experience and navigation efficiency of pedestrians.

2) For completed parking lots, areas that are easy for pedestrians to get lost can be identified by using the methods in this study. For example, through the analysis, it is found that the areas near entrance/exit 1 in this paper have the problem of low walking perception. For these areas, appropriate marking and indication systems are designed and set up, such as enhanced lighting, additional signage and guiding arrows in the area around entrance/exit 1, in order to improve the walking perception and safety of pedestrians.

3) In the daily operation of a parking lot, managers can use the methodology of this study, combined with real-time monitoring data, to respond to changes in parking rates. When parking rates increase during peak hours, walking perception decreases and managers can implement a series of temporary measures. As shown in Figure 12, walk perception decreases in the peripheral areas of the parking lot during hours when parking demand rises sharply. Managers can deploy additional on-site staff to provide orientation services in the peripheral areas. At the same time, considering that the entrances and exits are also areas of low walk perception, managers can optimize vehicle parking strategies near these key points. Adjusting the allocation of parking spaces, ensuring that the vicinity of entrances and exits remains unobstructed, as well as installing clear signage can minimize interactions between vehicles and pedestrians. These dynamic management measures can ensure that the parking lot maintains good operating conditions at different times of the day, providing a safe and convenient parking and walking environment for pedestrians.

References

1. Zhang Y Z, Bai Y. Internet of Things Based on Parking Lot System Design[J/OL]. Advances in Computer, Signals and Systems , 2023,7(10).
2. Jiang Z, Gao X, Li Y, Wang H, Zhang Y, et al. Multilayer map construction and vision-only multi-scale localization for intelligent vehicles in underground parking[J]. Measurement Science and Technology, 2022, 33(11): 115 021.
3. Shin B, Lee J H, Yu C, et al. Underground Parking Lot Navigation System Using Long-Term Evolution Signal[J]. Sensors, 2021, 21 (5): 1725 .
4. Ye Jianlin, Pan Zhihong, Yan Haohan. Indoor Intelligent Parking Navigation System Based on Ibeacon[J]. Journal of Computer Technology and Development, 2020, 30(3): 20 9–213.
5. Dai Wenhao, Du Feng. Analysis of fire evacuation problems in underground parking lot of urban railway[J]. Urban Rail Transit Research, 2023(S2): 190–194.
6. Zhang Shu, Shi Lihong, Zhao Xizhi. Data Fusion of Community Smart Parking from the Perspective of Scenarios[J]. Bulletin of Surveying and Mapping, 2023(3): 61–66.
7. Tan Zhongsheng, Wang Mengshu, Wang Yonghong, et al. Research on the Development Status and Construction Technology of Urban Underground Parking Lots in China[J]. Strategic Study of Chinese Academy of Engineering, 2017, 19(6): 100–110.
8. Wang Linjie, Shao Jizhong, Sun Zhenying, et al. Research on Walking Perception of Multi-layer Underground Rail Station Based on Space Syntax[J]. Industrial Construction, 2023, 53(4): 46-53+45.

9. Hillel Beer, Sheng Qiang. Development Status and Future of Space Syntax[J]. Architectural Journal, 2014(8): 60–65.
10. Wu Duan. Introduction to Spatial Syntax Related Theory[J]. World Architecture, 200 5(11): 10–15.
11. Qiu Yuqian, Chen Gang, Li Mengyue, et al. Research on the evolution of modern urban form in Gulou District, Nanjing from the perspective of syntax [J/OL]. Surveying, Mapping and Geographic Information,1-7.
12. Wu Yufei, Lin Jing. Research on the Improvement of Streets and Alleys in Historic Districts Based on Spatial Syntax: A Case Study of Guozijian Historic District, Beijing [J]. Urban Architecture, 2024, 21(5): 20-25+74.
13. Gui Wangyang, Zhang Xu, Zhou Xin. Research on the spatial characteristics of underground transfer of high-speed railway station based on space syntax[J].Chinese Journal of Underground Space and Engineering,2023,19(03):701-713.
14. Jiang Yifei, Zhang Honglei, Li Mimi, et al. Correlation study between the distribution of shared accommodation and urban functional space and road network morphology in Hong Kong [J]. Journal of Geo-information Science: 1–14.
15. He Lijie, Xu Minhui, Xu Weiguo. Multi-scale Spatial Analysis and Renewal Strategy of Wangping Coal Mine Wasteland Based on Space Syntax[J]. Industrial Construction, 2022, 52(12): 42-48+54.
16. He Xiaxuan, Mo Xianfa, Pan Yining, et al. Analysis of Dong Traditional Houses and Regional Culture Based on Spatial Syntax [J]. Industrial Construction, 2023, 53(3): 10 5–114.