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Measuring pedestrian flows in public spaces: Inferring walking for transport and recreation using Wi-Fi probes

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ABSTRACT

Differentiating transport and recreational walking in public spaces could promote the precise design of walkable public spaces for different walking demands to encourage more walking behaviors. However, previous studies mainly relied on field observations and self-reports, failing to quantitatively distinguish and depict the spatial-level usage of transport and recreational walking of all pedestrians passing by. This study proposed an approach based on the traffic counts and the number of pedestrians to infer transport and recreation walking in public spaces. A comparative experiment using Wi-Fi probes to collect pedestrian data in a gated residential community and a creative center in Beijing, China, was conducted to verify the applicability of this method. The results demonstrated that the transport walking index (the number of pedestrians) could portray the volume of transport walking, and the recreational walking index (average traffic counts of each pedestrian) could depict the proportion of recreational walking in public spaces. Two tests using different time threshold parameters and field observations verified the robustness of the results. Given the low-cost and long-duration observation, this method can potentially support the process of Post Occupancy Evaluation and Environment and Behavior research in more public spaces to make them more walkable.

1. Introduction

Walking is the most fundamental and daily physical activity, which plays an irreplaceable role in individuals' physical and mental health [1]. Dependent on different purposes, walking could be broadly divided into two types, namely, transport walking (also called utilitarian walking or instrumental walking), motivated by some destinations (e.g., to work, to a shopping mall, or some event) and recreational walking specifically for exercise or wandering [2–6]. Recreational walking, as an active physical activity, could provide substantial health benefits [7], boost long-duration staying behavior [8], encourage social network links and local social interaction [9], foster trust and reciprocity among individuals, and enhance social control and cohesion [10]. Meanwhile, as a "non-motorized transport", transport walking is a flexible, feasible, and low-carbon travel mode for utilitarian purposes, which could be environment friendly and promote sustainable city development. Therefore, in terms of the aforementioned benefits, despite the varied focus on forms and purposes for walking, scholars from public health [11,12], urban planning and design [5,13], and transportation [14] started to cooperate and make efforts to create more walkable streets, neighborhoods, and communities to encourage more walking activities [7].

Prior studies have shed light on many behavioral differences and diverse spatial preferences for transport and recreational walking motivations from the individual's perspective. Walking for transport has a defined destination and is shorter in duration, faster in speed, more continuous in pace, and more frequent than recreational walking [3,6], which is positively related to walking infrastructure [12], path segments well-connected in the path network [5], and areas with low average topographic slope [3] and specific and diverse destinations [3,5,12], but is less correlated with neighborhood design elements than recreational walking [13]. Recreational walking occurred more frequently in communities and neighborhoods [3,13], which highly correlated with neighborhood design elements such as aesthetics [12], attractive views, and well-connected path segments [5]. Regarding these significant differences in spatial preference of walking for different purposes, distinguishing transport and recreational walking in public space is the basis for identifying the demand for different walking activities to

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support corresponding walkable space design and the renewal of public spaces [15].

However, the state-of-art estimates differentiating walking for transport and recreation were mainly based on interviews, questionnaires [12,16], and self-reports [17], which precluded fine-grained and long-span investigations, hence limiting the in-depth examination of the spatial distribution of different pedestrian flows [3]. Although some studies based on self-reports also used wearable devices like handheld GPS [18], GPS built into other devices [19], and accelerometers [3] to help monitor walking behaviors and acquire continuous fine-grained tracks, they are costly and might be affected by the implications of experiments on individual perceptions and activities. Overall, although these individual-based data could help reveal the relationship between health outcomes and physical activities [17] and respondents' inner spatial preferences [20], they focused on individual-level space-time activities, failing to depict the spatial-level usage of all pedestrians passing by.

Recently, with the development of various sensors, some devices such as Bluetooth [21], Wi-Fi probes [22], infrared counters [23], and various camera video recorders [24–26], have been used to identify spatial usage in public spaces, which has the potential to help recognize distinct walking behaviors. The activity pattern in public spaces over a long time and the relationship between the built environment and activities [27] could be uncovered with the space-based data collected from the above devices. The existing studies in various scenarios, such as shopping malls, public transport stations, road intersections in communities, and scenic areas, focused on different information derived from data based on these devices. For example, studies in shopping malls and scenic spots analyzed the number of visitors, staying period, and frequent routes [28], and those in public transport stations paid more attention to the changes in the number of visitors across different time duration and passengers' wayfinding and trajectories [29]. However, few studies attempted to analyze walking activities from the synthesized perspectives of recreation and transport given the monotonicity of activity (dominated by transport walking or recreational walking) in the aforementioned study areas.

To address this critical gap, we proposed a method based on the traffic counts and number of pedestrians to infer transport and recreational walking in public spaces quantitatively. We took a residential community as the main experiment and a creative center as the comparative one in Beijing, China, to verify the applicability of this method using the data collected from Wi-Fi probes. We described the methodology in the next section, including the method, experiment design, study area, and data collection and processing methods. Then, we illustrated and compared the results in these two study areas to examine the applicability of this method in explaining the spatiotemporal patterns of recreational and transport walking in these areas. Two robustness tests were conducted to check the stability of the results using different parameters and verify the results with field observations. Finally, we discussed the method's contribution, potential application and applicable scenarios, and environmental constraints and limitations.

2. Methodology

2.1. Method to distinguish transport and recreational walking in public spaces

This study aimed to distinguish transport and recreational walking in public spaces in a quantitative way. As described above, walking for transport has a defined destination and is shorter in duration, faster in speed, more continuous in pace, and more frequent than recreational walking [3,6]. Therefore, this study proposed the definition of transport and recreational walking from the space perspective: transport walking is a trip with fewer crossings and fewer short stops during a day, while recreational walking is a trip with a longer staying or more crossings during a day. Based on the definition, this study proposed a method to calculate the volume of transport walking and the proportion of recreational walking in public spaces based on traffic counts and the number of pedestrians in a specific site at a certain time interval throughout the day (Fig. 1).

For transport walking, each pedestrian would traverse the area only once (one-way trip) or twice (round trip) a day in most situations at a relatively higher speed. Given that pedestrians may take different paths when arriving and leaving, the traffic counts to the number of pedestrians in a public space tend to be closer to 1 for most spaces in alternative paths (for unique entrances and exits, the number is 2). Therefore, this study used the number of pedestrians across the area as the index to reflect the volume of transport walking, even though it does not record the exact transport flows. The higher index value indicates more transport walks in this public space, reflecting the value of space for transportation and commuting.

During recreational walking, a pedestrian may wander, stay or repeatedly cross the study area numerous times, resulting in substantially more traffic counts than the number of pedestrians. That means public spaces with a higher ratio of traffic counts to the number of pedestrians have a higher proportion of recreational walking. Therefore, this study took the average traffic counts of each pedestrian as the index to measure the proportion of recreational walking. When this index approaches 1 (for most spaces in alternative paths), it suggests few recreational walks in the space; otherwise, it indicates a higher proportion of recreational walking.

To understand these two indexes more directly: the higher transport walking index represented by the number of pedestrians means more people choose to pass through the space, indicating that the space has a more critical position in the traffic node. In comparison, the higher recreational walking index could be explained as people wandering around the space or staying for a longer time, thus suggesting that the space has higher attractiveness for recreational activities.

Notably, this study used the two indexes to describe the space-level walking features rather than infer the purpose of each specific trip. For example, for a specific person, a trip in the observed space cannot be categorized absolutely as transport walking; similarly, his multiple times of passing by do not definitely mean he is walking for recreation. Although it is difficult for us to directly judge the travel purpose of each person's every trip from the Wi-Fi data, we can identify the main function of the public space and the importance of the space for transportation and recreation via these two indexes.

2.2. Experiment design

This study proposed a four-step framework for the experiment to collect and process data, verify the method's applicability in explaining the spatiotemporal patterns of the two types of walking behaviors, and test the robustness of results using alternative parameters and field observations (Fig. 2).

This study collected pedestrian data using Wi-Fi probes to acquire traffic counts and the number of pedestrians. There are three main reasons for us to choose Wi-Fi probes. First, smartphones with Wi-Fi enabled always send out probe requests with unique MAC addresses-the unique string of hexadecimal integers-enabling the Wi-Fi probes in the public space to detect pedestrians carrying mobile phones with Wi-Fi enabled. By calculating Wi-Fi probe requests, we can derive traffic counts by adding the total number of mac addresses for all devices and the number of unique mac addresses to determine the number of pedestrians. Second, since the Wi-Fi probes only acquired the MAC address of smartphones, the generation of pedestrian data from Wi-Fi probes is usually anonymized, which avoids personal privacy issues. Third, this method using Wi-Fi probes could be applied in some places where Wi-Fi access points are already installed in the environment or residential communities that have the potential to provide free Wi-Fi in public spaces soon.

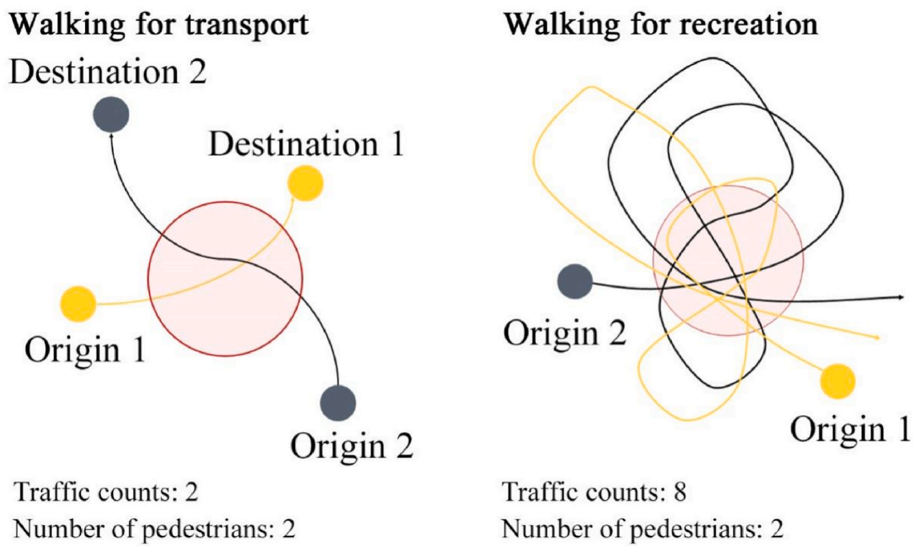

Fig. 1. The different patterns of traffic counts and the number of pedestrians in transport and recreational walking.

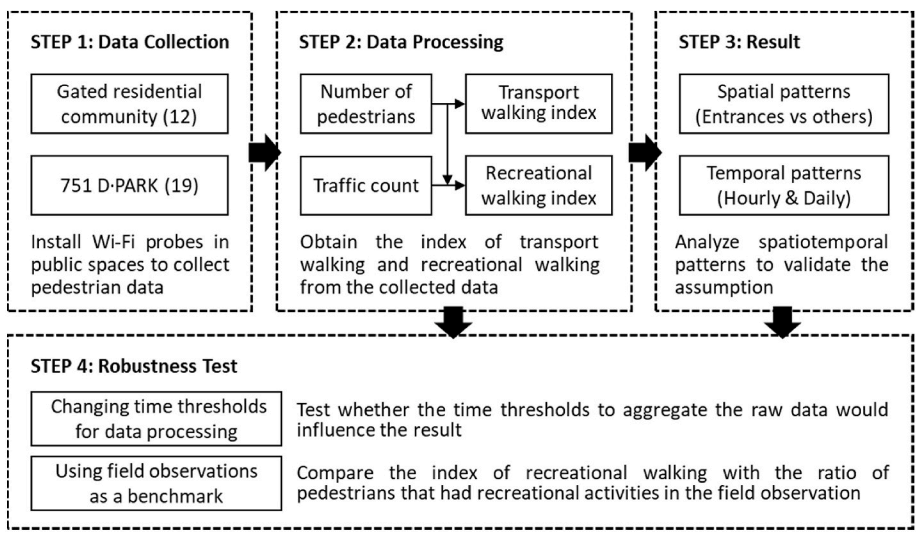

Fig. 2. The framework of the experiment design.

After collecting all pedestrians' MAC addresses, this study extracted the traffic counts and the number of pedestrians to generate the transport and recreational walking index, respectively. Then, the spatiotemporal patterns of these two indexes were analyzed by comparing their difference in entrances and other places, and observing the changes of values between hours in the day, weekdays, and weekends. Finally, this study changed the time thresholds for data processing to test whether the thresholds would influence the result, and used field observations as a benchmark to examine the accuracy of this method.

2.3. Study area

To better validate the applicability of the method mentioned above, this study chose a residential community for the main experiment and robustness tests since it consists of more complicated and mixed walking behaviors than other places [30]. As basic living units, residential communities could witness residents' all the transport walking from their homes to other destinations such as working places, city centers, hospitals, and shopping malls. Meanwhile, as the most frequently used places for daily activities, residential communities also carry much recreational walking and activities. Therefore, the residential community is an ideal experiment object to differentiate walking for transport and recreational purposes. Besides, this study also chose a creative center for the comparative study to examine the application of this method in other places and verify the significance and particularity of differentiating transport and recreational walks in public spaces in the residential community. Therefore, we selected a gated residential community (Site 1) and a creative center (Site 2) in Beijing, China, for comparative research (Fig. 3).

The gated residential community (0.13 km^2) is located in Tongzhou, the sub-center of Beijing, with 3000 residents, which is adjacent to the main road on the south, a linear park along the river on the north, and two other residential neighborhoods on the east and west. We chose this gated residential community for the main experiment for three reasons. First, the gated residential community is the main form of real estate in China and thus is the most typical one of Chinese residential communities. Therefore, the selected gated community in this study could be representative of other residential communities, especially gated ones. Second, since this community is gated, fewer other pedestrians walk through it, reducing the impact of the activity and spatial preferences of other pedestrians on the data collection of this study. Third, there is no grocery stores, café, or other points of interest that may serve as

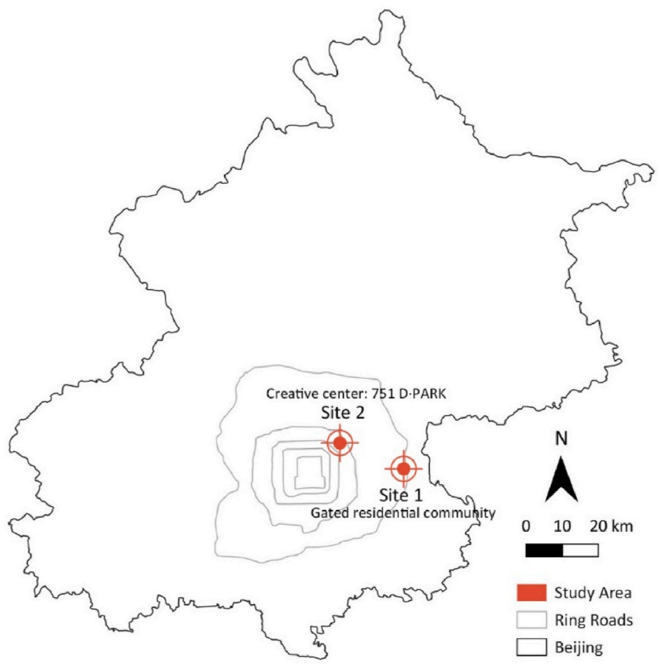

Fig. 3. The location of the study areas in the experiment.

destinations for transport walking inside the selected residential community, ensuring the residents' walks for transport purposes mainly toward residential entrances and avoiding the impact of short trips to other destinations on the results.

The creative center- 751 D·PARK (0.22 km^2), dominated by offices and indoor exhibitions, was selected as a comparative experiment. It is situated in Chaoyang District, Beijing, surrounded by workplaces on the east, south, and north and adjacent to the 798 Art Centre on the west. We chose this creative center in terms of its similarity to the selected residential community, which is also gated and mainly carries walking behaviors, avoiding the impact of passing vehicles and pedestrians on the results. Besides, compared to parks, squares, or scenic spots, the creative center is also a building-based area with many public spaces. These similar situations ensured that the results in these two study areas were comparable.

2.4. Data collection

Considering that the Wi-Fi probe is more sensitive to pedestrian detection in outdoor environments than indoor buildings, we encased the Wi-Fi probe in a lockable, watertight plastic box to protect it from theft and extreme weather and simultaneously guarantee the convenience of maintenance. The integrated device was marked with a "Monitoring Network Equipment Box" label to ensure the data collection was transparent for pedestrians. The integrated device was installed about 2 m above the ground on the surrounding utility poles, fences, and trees in the observed public space and was continuously powered (Fig. 4). In this way, each Wi-Fi probe was powered by electric wires connected to the power supply and constantly collected pedestrian data every 5 s around the clock. The pedestrian data acquired from Wi-Fi probes was uploaded to an online server every 8 h (three times a day) via wireless LAN drivers. Pre-experiment results showed the device's detection range in outdoor space was 25 m. The installation of Wi-Fi probes was permitted and supported by the local administration-the Beijing Wuyi Real Estate Development Co., Ltd. in the gated community and Beijing Zhengdong Electronic Power Group Co., Ltd. in 751 D·PARK.

We deployed 12 Wi-Fi probes in the gated residential community and 19 in 751 D·PARK to collect pedestrian data for this study. The Wi-Fi probes were utilized to scan the main public spaces, including the green corridor, exercise area, transition space, road intersections, and main entrances. For the gated residential community, Wi-Fi probes Nos.1, 5, 9, and 12 were deployed near the community's northwest,

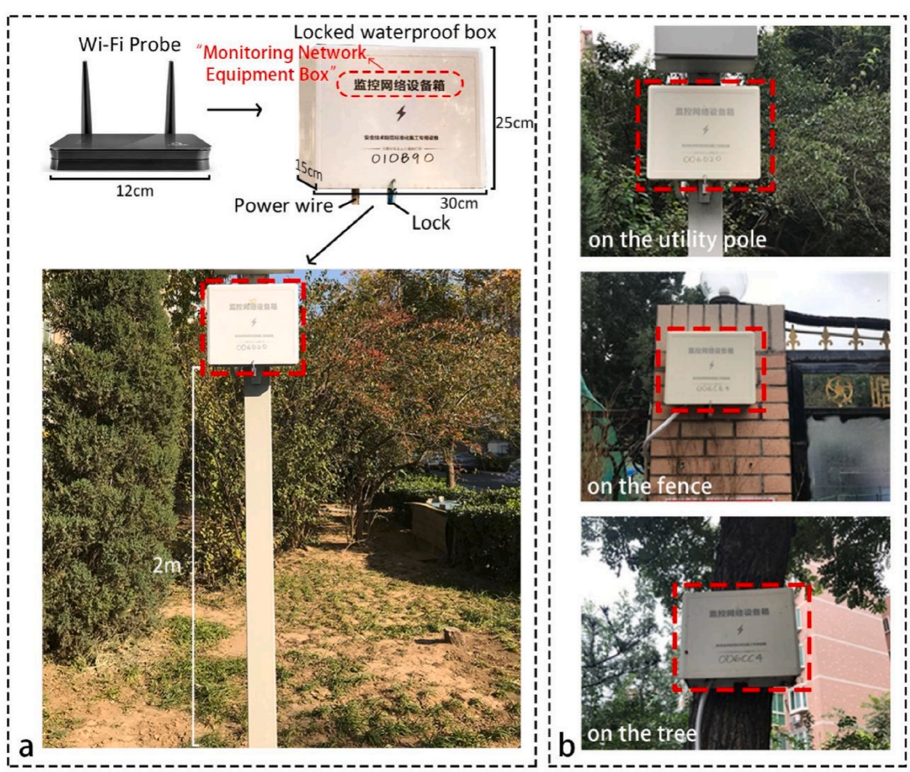

Fig. 4. The demonstration of the integrated Wi-Fi device box (a) and its installation (b).

southwest, south, and southeast entrances to collect data on pedestrians entering or exiting. Additionally, the Wi-Fi probes Nos.2, 3, 4, and 5 were placed to monitor persons moving down the community's "boulevard". The Wi-Fi probes Nos.6 and 7 were installed to monitor pedestrians in the community's "central garden". Walkers were spotted wandering down the community's promenade in the south using Wi-Fi probes Nos. 8 and 9. The Wi-Fi probes Nos.10 and 11 were used to collect data from walkers using the sidewalk next to the high-rise residential complex (Fig. 5-a). The period of data collection was from August 1st, 2018, to April 30th, 2019.

For 751 D·PARK, the comparative analysis, Wi-Fi probes Nos.1, 2, 8, 18, and 19 were installed in the main entrances of this area. The Wi-Fi probes Nos.9 and 17 were placed near the parking lot, and Nos.12, 13, and 14 were installed near the designer building to monitor pedestrians. Nos.15 and 16 detected individuals who entered the area of Tower A of the Beijing Fashion Design Plaza. Nos.3, 5,.6, and 7 were used to record people entering or leaving several essential venues. Nos.4, 10, and 11 were installed at road intersections (Fig. 5-b). The data collection period was from August 26th to September 9th, 2018.

2.5. Data processing

After collecting the smartphone MAC addresses for all the pedestrians carrying smartphones with enabled Wi-Fi (dropping the MAC

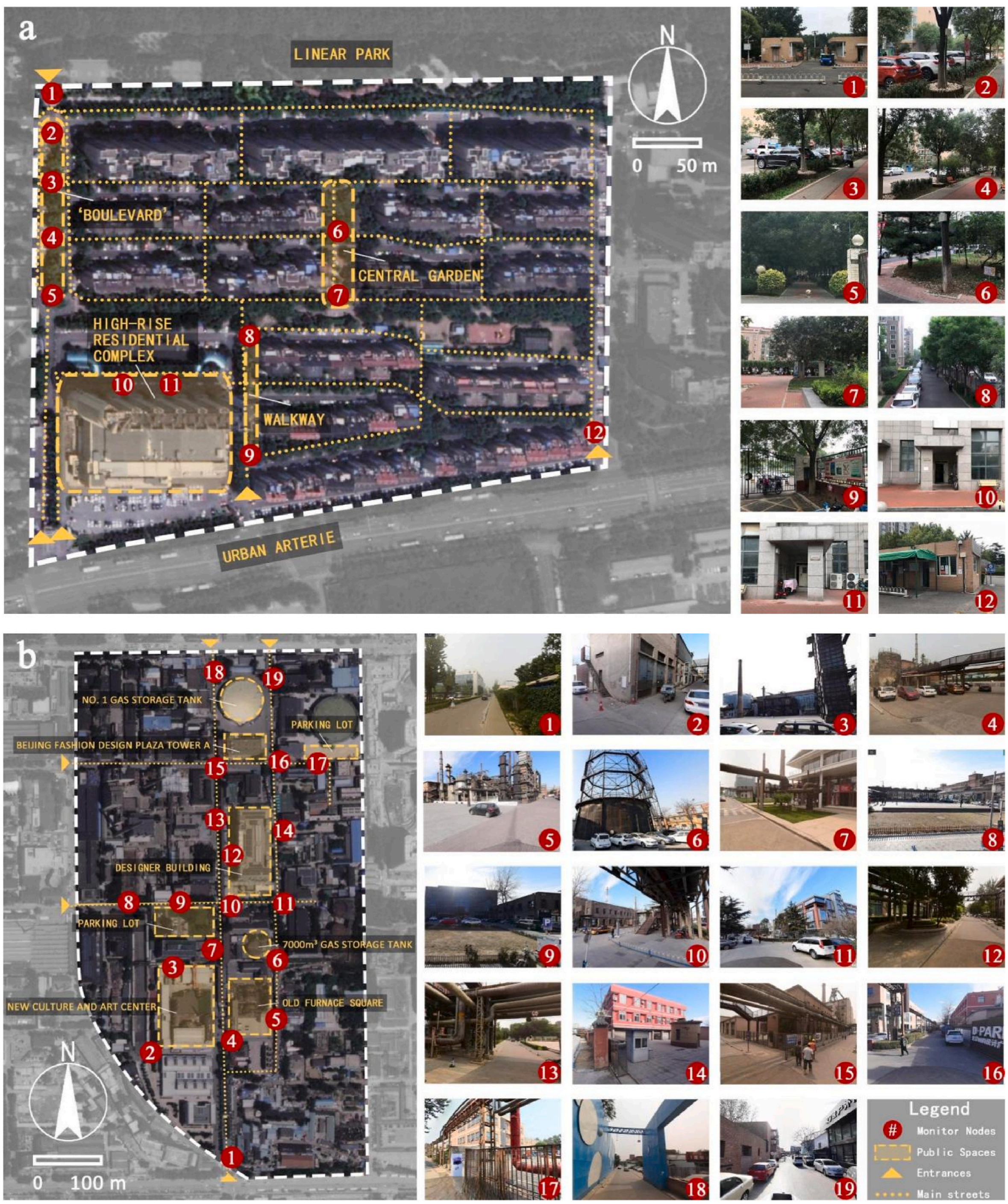

Fig. 5. The installation location of Wi-Fi probes in the gated residential community (a) and 751 D·PARK (b).

addresses of surrounding fixed Wi-Fi routers), this study conducted three steps to process the raw data (Fig. 6).

First, this study dropped the duplicate data of the same Wi-Fi probe recorded in the 1 min to ensure pedestrians walking through the detective range of the Wi-Fi probe for transport purposes was recorded once, and someone having a long-duration wandering or staying with more traffic counts. The reason for using 1 min as the threshold in this study was based on two considerations. The first one was the time for pedestrians to pass by the detective range of the Wi-Fi probe. Considering that the Wi-Fi detection range is 25 m and the per capita walking speed is 1.2 m/s (the old and disabled might walk even slower), the time required for a person to pass by the Wi-Fi detection range is about 20s. The second one considered the short stops during the transport walking. As Gehl [31] stated in *Life Between Buildings*, some short stops, such as stopping to fix something, stopping to look at something, and stopping to avoid vehicles and pedestrians, were not included in staying behaviors or recreational activities. According to the pre-experiments of this study, these short stops were usually no longer than 30 s. Therefore, this study used 1 min as the time threshold to clean the raw data, which could avoid generating more traffic counts due to the detection range of Wi-Fi, slow walking of the old and the disabled, and short stops during transport walking.

Second, this study calculated the number of unique MAC addresses as the number of pedestrians and summarized the total MAC addresses as traffic counts. Then, the number of pedestrians was regarded as the transport walking index, and the average traffic counts of each pedestrian were considered as the recreational walking index to describe the walking behavioral characteristics of each public space. The public spaces with higher traffic counts might serve as the vital traffic nodes, such as entrances and the main traffic channels, while places with higher average traffic counts of each pedestrian witness a higher proportion of recreational walking.

3. Results

3.1. The spatial patterns of the two walking indexes were consistent with the main function of the public spaces

In the gated residential community, the average daily number of pedestrians for each Wi-Fi probe ranged between 500 and 3,000, and traffic counts ranged between 3000 and 7000 (Fig. 7-a). The association

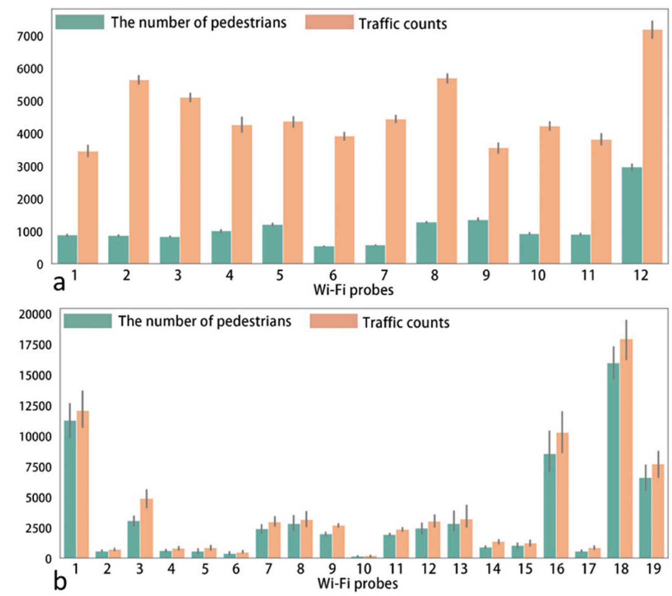

Fig. 7. The average daily number of pedestrians and traffic counts of each Wi-Fi probe in the gated residential community (a) and 751 D·PARK (b).

between average daily traffic counts and the number of pedestrians was not apparent for all Wi-Fi probes, indicating that the pedestrian flows in these public spaces had distinct spatial patterns. The spatial patterns of the daily transport walking index and the recreational walking index could reflect the primary function of the public spaces. The transport walking index was high at the community's entrances (Nos. 5, 9, and 12), while the recreational walking index was relatively low. This phenomenon could be explained that the areas near the community entrances had more transport walks and prevented people from having more recreational walking. Meanwhile, people tended to take more recreational walking in the inner places of the community; therefore, the recreational walking indexes in those places, such as Nos.2, 3, 6, and 7 were also high (Fig. 8-a).

In the 751 D·PARK, the average number of pedestrians detected by Wi-Fi probes ranged from 200 to 16,000, while the range of traffic counts was from 200 to 17,500 (Fig. 7-b). The transport walking index

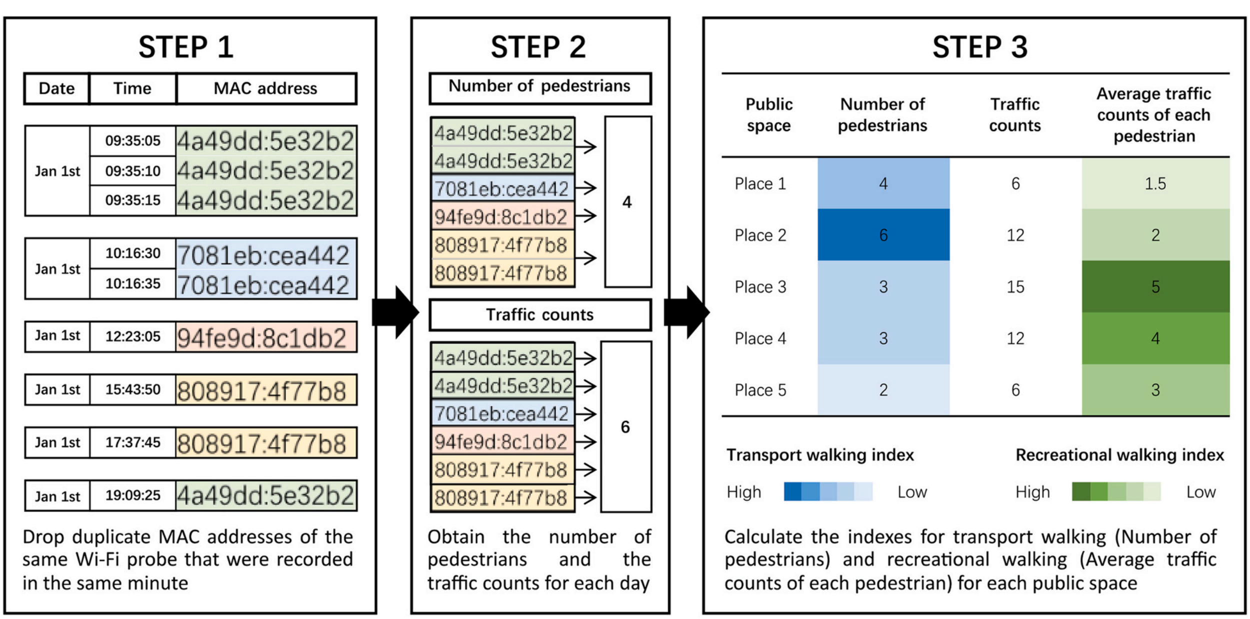

Fig. 6. The three steps to process the raw data collected from Wi-Fi probes.

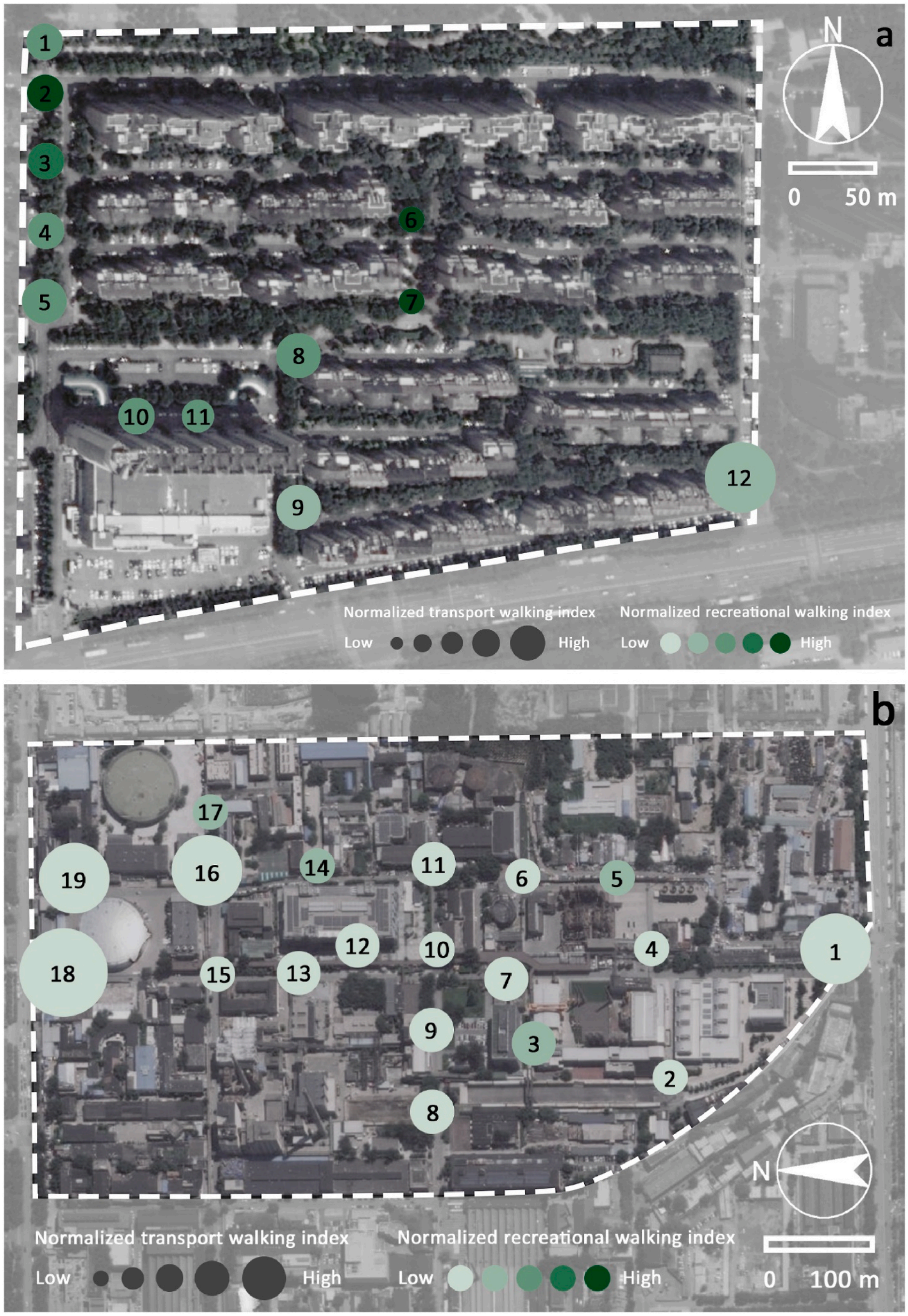

Fig. 8. The spatial patterns of the normalized transport and recreational walking index in the gated residential community (a) and 751 D·PARK (b).

was high in the north and south entrances (Nos. 1, 18, and 19), while the recreational walking index in most public spaces was low, suggesting that tourists prefer to pass by rather than stay or wander in these areas (Fig. 8-b). The results indicated that the observed outdoor public spaces in the 751 D·PARK primarily act as transportation connections between various buildings. That means pedestrians walking through these areas aimed to reach other places or buildings, making these places serve as transport networks. The result is reasonable because 751 D·Park is a creative center composed of various buildings transformed from industrial facilities and settings, which now serve as venues for design events and exhibitions. Therefore, pedestrians walking in outdoor public spaces in 751 D·Park have a defined purpose, resulting in less stopping and wandering than those in residential communities.

Overall, according to the spatial distribution, the recreational walking index could reflect the residents' preference for recreational activities, while the transport walking index could imply the importance of public space for transport walking. The higher transport walking index at the entrances in these two study areas suggested more traffic walks in these public spaces, while a relatively higher recreational walking index in some inner public spaces implied their greater attractiveness for individuals to conduct recreational activities.

Fig. 9 compares the normalized average daily number of pedestrians and traffic counts collected from Wi-Fi probes between the gated residential community and 751 D·PARK. Wi-Fi probes closer to the diagonal lines in the figure detected more transport walks (the recreational walking index was close to 1), while more recreational walks were observed from Wi-Fi probes further away from the diagonal line (with a higher recreational walking index). The results showed that most Wi-Fi probes, except for No. 3 in 751 D·PARK, mainly monitored transport walks, suggesting similar functions of these observed public spaces. In

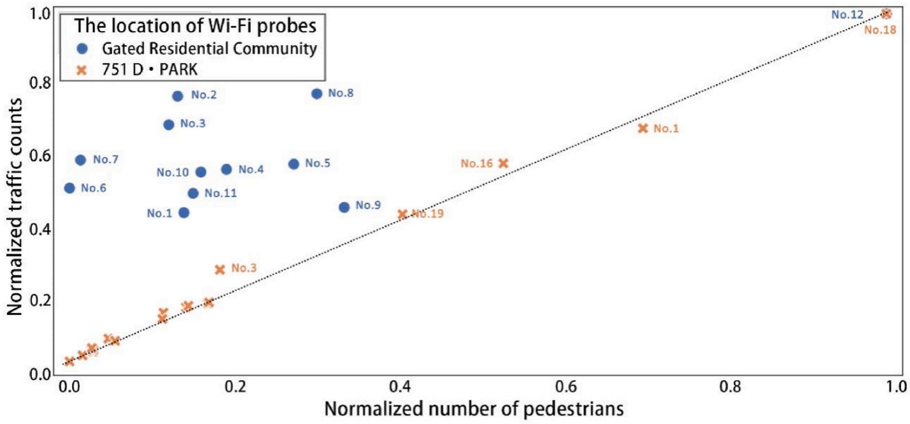

Fig. 9. The normalized average daily traffic counts and the number of pedestrians of each Wi-Fi probe in the gated residential community and 751 D·PARK.

comparison, the performances of data acquired from Wi-Fi probes in the gated community varied greatly: Nos.9 and 12 were near the diagonal line, while Nos. 2, 3, 6, and 8 were further away from the diagonal line. In view of the significant differences in the recreational walking indexes (the traffic counts divided by the number of pedestrians) among public spaces in the residential community and the similar recreational walking indexes (all close to 1) in 751 D·PARK, the results revealed that public spaces in the residential community composed of different proportion of recreational walking and played diversified roles in guiding different walking behaviors, suggesting more complicated and mixed walking behaviors in residential communities than the office and exhibition-oriented creative center.

3.2. Two walking indexes could reflect the temporal characteristics of transport and recreational walking

The temporal rhyme for transport and recreational walking would ordinarily vary significantly during the day and the week. Specifically, for the residential community, the proportion of recreational walks should be high during the daytime on weekdays and weekends, and the volume of transport walking should be incredibly high in the commute period in the morning and afternoon on weekdays and also high in the late morning on weekends. For the creative center, the volume of transport walking continues to increase in the morning and decrease after activity events or closures in the evening, and the proportion of recreational walking would depend on the attributes of the public spaces in the area. To verify whether the data we generated in this study could reflect the temporal pattern of recreational and transport walking, we

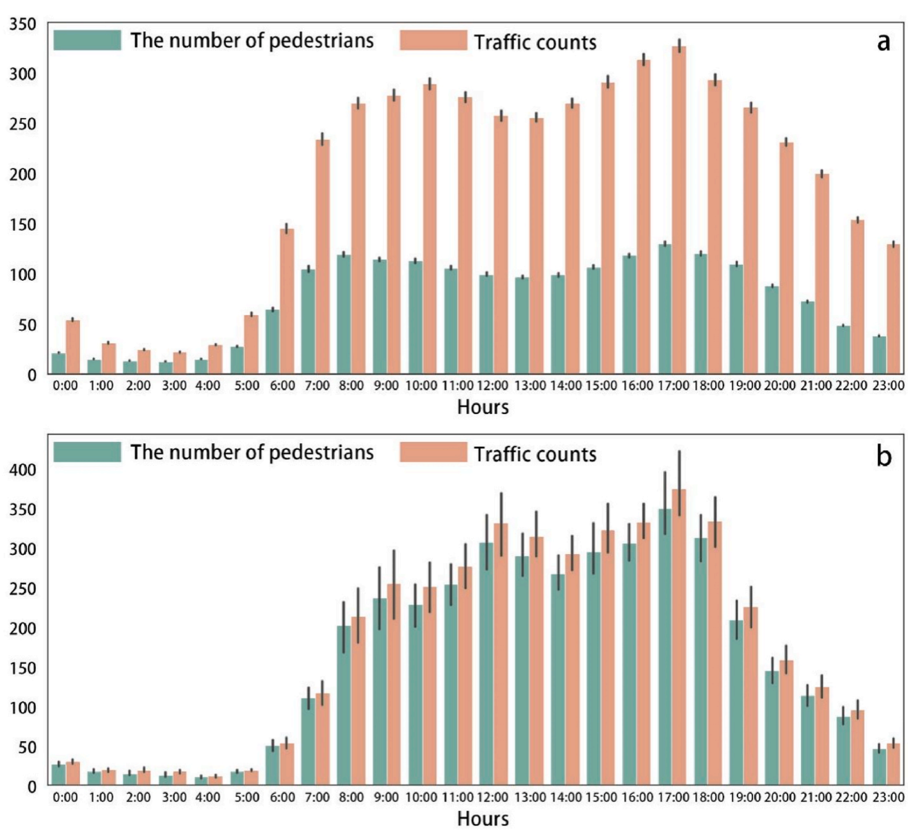

Fig. 10. The average number of pedestrians and traffic counts by hours in the gated residential community (a) and 751 D·PARK (b).

summarized and compared the number of pedestrians and traffic counts by hours and weekday/weekend.

3.2.1. *Comparison between different hours in a day*

This study compared the average number of pedestrians and traffic counts at different hours of the day, which showed different patterns in the two case areas, suggesting their differentiated functions and diversified spatiotemporal walking behaviors (Fig. 10).

In the gated residential community, the transport walking index demonstrated a tidal effect and peaked at 8:00 and 17:00. While the traffic counts peaked later in the morning and reached the peak at 17:00. The recreational walking index was smaller during 1:00–8:00 a.m. and 16:00–18:00 than during 9:00–15:00 and 19:00–0:00. The results implied that in the residential community, the leading role of these public spaces was for transport walking in the early morning and commute time in the afternoon, while there was relatively more recreational walking during the most of the daytime and night. In the 751 D·PARK, the transport walking index peaked at 12:00 and 17:00 in public spaces, which was the time for lunch and dinner. In the morning, the values rose steadily before noon, followed by a slight decrease during 12:00–14:00, and then increased continually until 17:00. After the numbers dropped dramatically during 18:00–19:00, they decreased stalely. The similar values between the number of pedestrians and traffic counts indicated that the recreational walking index was close to 1 at most times of the day, suggesting that people walked through these areas for transport purposes.

The results between the gated residential community and 751 D·PARK complied with the activity rules of both venues. The residential community carried more recreational walking and witnessed two striking commuter flow peaks since it also had plenty of residents' transport walking in the morning and afternoon. In comparison, the office and exhibition-oriented creative center saw fewer recreational activities in the public space since pedestrians targeted various offices and exhibition buildings. Besides, in terms of the duration of various events, people may arrive in succession but leave after the event, so there is no obvious arriving peak in the morning, but a significant departure peak at the end of the day and a secondary departure peak at the end of the half day. Overall, the results suggested that the method proposed in this study could reflect the characteristics of transport and recreational walking during the day. The results also indicated that the higher recreational walking index in the residential community suggested more recreational walking in the residential community than in 751 D·PARK. Therefore, the differences in the proportion of transport and recreational walking could help understand the leading function of the whole area and every public space.

3.2.2. *Comparison between weekdays and weekends*

Fig. 11 shows temporal patterns of the transport and recreational walking indexes on weekdays and weekends. For the gated residential community, the transport walking index was high at 8:00 on weekdays but peaked at 11:00 on weekends, indicating that the traffic flow appeared later in the morning on weekends. Besides, the recreational walking index was higher in the morning and night but lower in the afternoon on weekends than on weekdays. Therefore, how the transport and recreational walking indexes changed on the weekdays and weekends showed a similar pattern to transport and recreational walking. For the 751 D·PARK, the differences in the transport walking indexes between weekdays and weekends suggested different behavior characteristics. One possible explanation of this phenomenon is that people visited 751 D·PARK for the whole day on weekends, while on most weekdays, people only participated in half-day activities. The recreational walking index in 751 D·Park among various hours were all similar and close to 1.0, reflecting walking for transport purposes at all times.

Overall, the spatiotemporal heterogeneity of the transport and recreational walking indexes reflects the disparity between the spatiotemporal preferences for transport and recreational walking. The different spatial performance of the two indexes among various public spaces and between these study areas could depict their primary functions and attractiveness for recreational and transport walking. The variations of the two indexes among different times of the day and between weekdays and weekends indicated the applicability of the method proposed in this study could be used to infer and depict the space-time behavior in different kinds of public spaces.

4. Robustness test

4.1. *Results using different time thresholds to process the raw data*

Since this study used 1 min as the threshold to calculate the traffic counts and the number of pedestrians, the alternative selection of the interval parameter would not change the number of pedestrians (transport walking index), but might influence the value of traffic counts

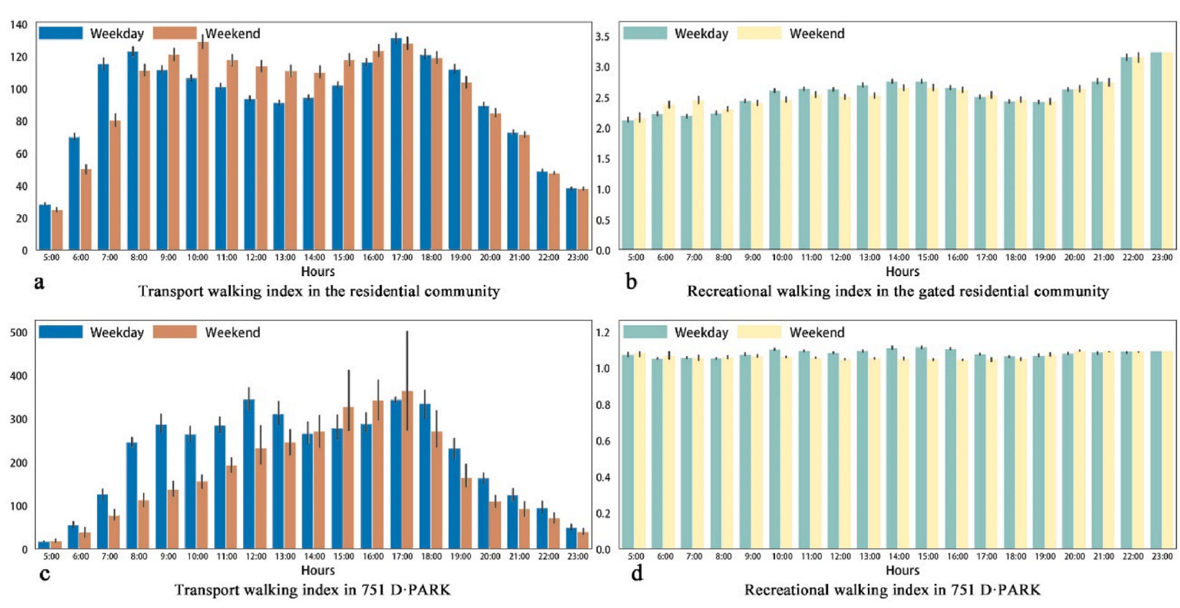

Fig. 11. The difference in transport and recreational walking indexes between weekends and weekdays in the gated residential community (a, b) and 751 D·PARK (c, d).

and further influence the recreational walking index. Therefore, this study used 1 min, 2 min, 5 min, and 10 min to process the raw data to compare the recreational walking index with different thresholds. Fig. 12 shows that although the recreational walking index decreased with the interval thresholds changed from 1 min to 10 min to process the data, the differences among most observed public spaces (except for Wi-Fi probe Nos. 1 and 8 in the 10-min threshold) presented similar patterns, suggesting that the threshold used in this study would not interfere with the comparison of the recreational walking index among different public spaces.

4.2. Results using the field observations as the benchmark

Since the number of pedestrians was commonly used in previous studies to indicate the transport volume, the transport walking index was relatively reliable. Therefore, to verify that the recreational walking index could be used to describe the proportion of recreational walking in the public space, we conducted a field observation as a benchmark to examine the reliability of the recreational walking index. Considering that the residential community presented more complicated walking activities than the creative center in the outdoor public spaces, this study selected the residential community as the study area to conduct the robustness test.

Specifically, we collected the pedestrian data in the morning (9:00–11:00) and afternoon (14:00–16:00) on October 4th, 2018 (Thursday in the autumn), and April 14th, 2019 (Sunday in the spring) by simultaneous manual and video recording. The observation period lasted 15 min for each site in the single observation. Eventually, we obtained four manual records and 1 h of video data for each monitored area. We observed and counted the number of pedestrians who passed through the five areas where Wi-Fi probes were installed (Fig. 13) and recorded whether they engaged in recreational activities (e.g., staying, playing, chatting with others, and wandering) based on our subjective judgment according to the manual records and video data. Then we calculated the proportion of all pedestrians who had recreational activities.

We accumulated the average daily traffic counts and the number of pedestrians collected from Wi-Fi probes installed within the observed areas (Fig. A.1 in the Appendices). Then, we calculated the recreational walking index and compared it to the observed ratio of recreational walking in the field observation (Table A1). The result showed that the recreational walking index proposed in this study was significantly and positively associated with the observed ratio of pedestrians that had recreational activities (R^2 is higher than 0.9) (Fig. 14), confirming that the recreational walking index could reflect the proportion of recreational walking.

5. Discussion

5.1. Contribution

In view of the distinct spatial preference of transport and recreational walking, differentiating transport and recreational walking in public spaces could facilitate the assessment of spatial usage and identification of the different walking demands, thereby supporting the optimization of corresponding planning and design to make public spaces more walkable. However, state-of-art studies on distinguishing the two kinds of walking behaviors are mainly based on respondents' self-reports and researchers' observations, failing to achieve a long-term and fine-scale measurement of walking behaviors in a specific space. Meanwhile, emerging studies using various sensors and quantitative methods for public spaces focused on the count of pedestrians for the volume or the staying duration of visitors, ignoring distinguishing the recreational and transport walking in public spaces.

The novelty of this study is that we provided a novel approach based on the traffic counts and the number of pedestrians to quantitatively differentiate and depict transport and recreational walking in public spaces, which could be applied for a prolonged observation at relatively low costs. The experiments in two study areas in Beijing, China using Wi-Fi probes to collect the pedestrian data verified the applicability of the method and presented the way to analyze the data. Although this study used the residential community for the main experiment, this method could also be expanded to other public spaces to help increase the walkability of public spaces for different walking demands to stimulate more walking activities.

5.2. Potential applications and applicable scenarios

This method could be applied in Environment and Behavior studies to enhance insights into walking behaviors by providing data for understanding the spatiotemporal characteristics of residents' different walking behaviors in public spaces and the interactions between built environment elements and pedestrian behaviors. Considering that Wi-Fi probes could serve as the infrastructure of public spaces, this method also has the potential to improve the walkability of neighborhoods and communities by enabling urban designers and local administrators to examine the composition of transport and recreational walking, compare the attractiveness of various public spaces in guiding recreational activities, identify the actual primary function of the space, estimate whether the public spaces met the design purpose, and uncover spatial problems to support Post Occupancy Evaluations (POE).

Since the results demonstrated more complicated and mixed walking behaviors in residential communities, differentiating between transport

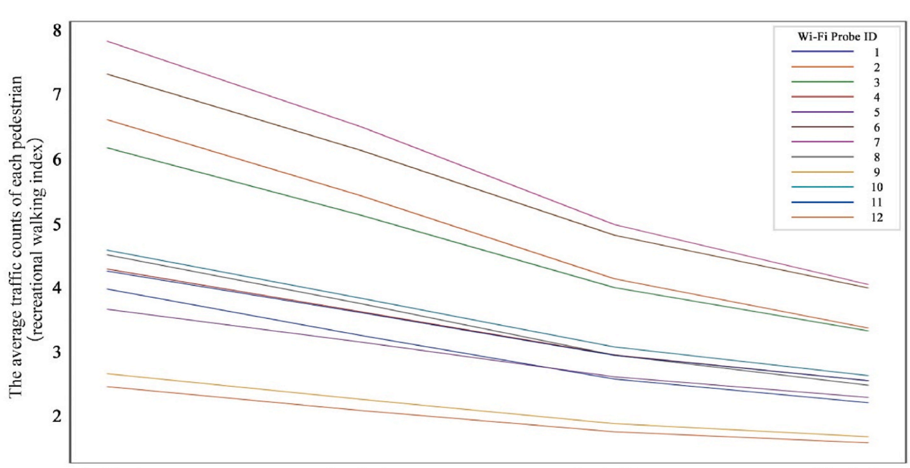

Fig. 12. The recreational walking index using different time interval thresholds to process the raw data.

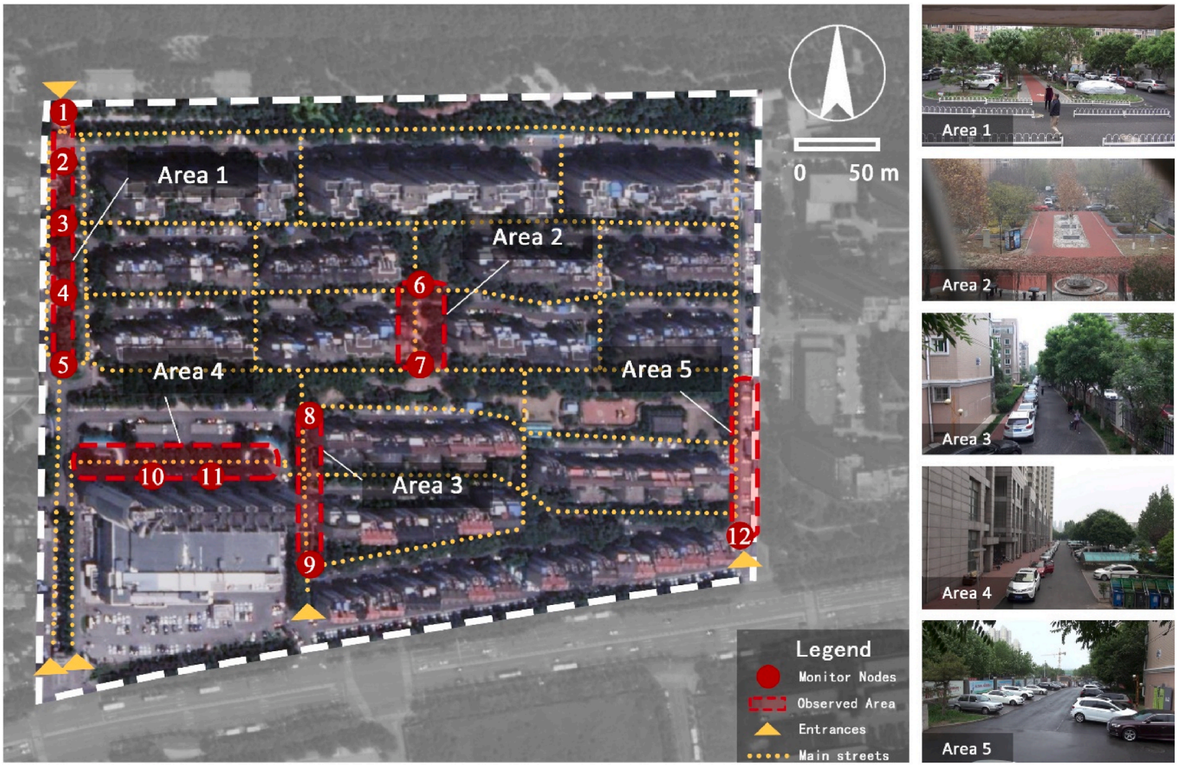

Fig. 13. The installation location of Wi-Fi probes and the observed areas in the field observation.

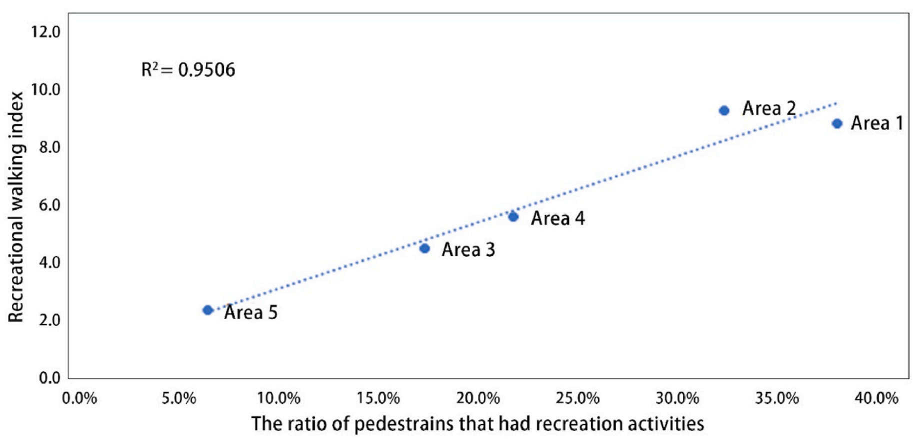

Fig. 14. The correlation between the recreational walking index in the Wi-Fi experiment and the ratio of pedestrians that had recreational activities in the field observation.

and recreational walking behaviors and their spatial preferences in residential communities is the most directly applicable scenario for the method proposed in this study. Besides, this method could also be applied to other places that might also have mixed walking behaviors, such as squares and plazas near office buildings or the city center, vest-pocket parks in the corner of streets, and other activity venues near traffic lanes. This method could help explore the temporal patterns of walks with different purposes and examine the attractiveness of these places for recreational activities in controlling the transport walking. Moreover, the distinction between these two kinds of walking behaviors can also reflect the attributes of different areas: those with diversified performances are accompanied by complicated functions, and those with similar ones have an apparent dominant function.

5.3. *Environmental constraints and more chaotic conditions*

There are some constraints and limitations to this method. First, both experiment areas in this study are gated to some certain extent, excluding some vehicles and pedestrians passing by the area. Therefore, there might be restrictions when this method is applied to open areas or those with more complicated points of interest for pedestrians as destinations. Some efforts should be made to adapt this method to different scenarios, such as excluding staff who frequently pass by these areas and deploying more Wi-Fi probes near relevant destinations to exclude the growth of the recreational walking index caused by multiple traffic walks. Second, since Wi-Fi probes were used to collect pedestrian data, this study ignored some pedestrians, such as the elderly and children without smartphones and pedestrians without Wi-Fi enabled in smartphones. Meanwhile, some mobile devices may change the mac address as time passes, increasing the transport walking index and reducing the recreational walking index in this study. Third, when the method is applied in other public spaces in areas with high vehicle flow, the results might be affected by smart devices in the car on the roads. When installed in some lush forests, plenty of plants may block the detection range of Wi-Fi probes. Therefore, the applicability of this method in more kinds of public spaces needs to be further examined with more types of experimental space.

6. Conclusions

In this study, we proposed a novel approach to effectively and quantitatively differentiating transport and recreational walking in public spaces. Motivated by the characteristics inherent in transport and recreational walking, this study used the differences in the traffic counts and the number of pedestrians in a given area within a certain period to infer and distinguish these two walking behaviors in public spaces. Specifically, we assumed that the average traffic counts of each pedestrian could depict the proportion of recreational walking, and the number of pedestrians was a proxy for the volume of transport walking. Compared to existing methods mainly based on volunteer-based experiments and self-reports, this study could achieve the prolonged observation of public spaces and distinguish different walking purposes at the space level so as to explore the spatial preferences of different behaviors, identify the primary function of the space, and assess the matching degree between the spatial usage and the design scheme, and further promote the precise design for walkable spaces.

Comparative experiments were conducted in several open public spaces in two typical areas using Wi-Fi probes to collect pedestrian data in this study. According to the spatiotemporal patterns of transport and recreational walking indexes and the robustness tests using different time thresholds to calculate the indicators and the benchmark based on field observation, the results demonstrated the two indexes could depict the spatiotemporal characteristics of transport and recreational walking in public spaces. This method has great potential to support fine-scale Environmental Behavior research and the POE in public spaces, especially for those in residential communities verified with more complicated and mixed walking behaviors in this study.

CRediT authorship contribution statement

Jingxuan Hou: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Enjia Zhang:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Ying Long:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

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

The authors do not have permission to share data.

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Appendices.

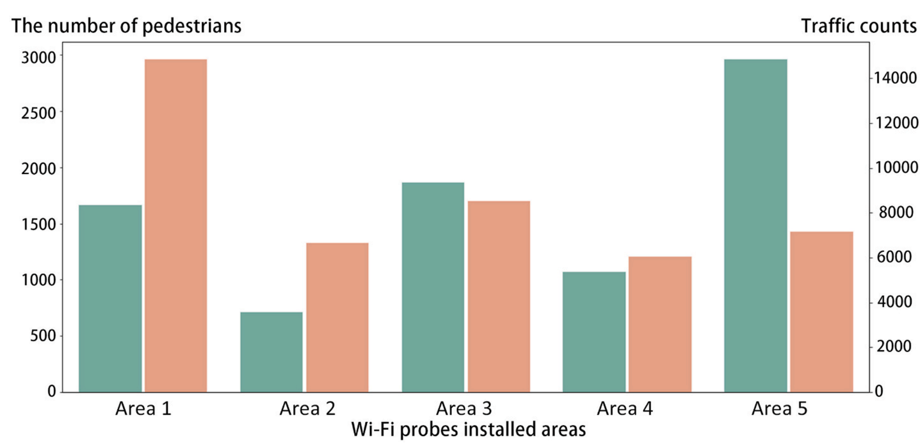

Fig. A.1. The average daily number of pedestrians and traffic counts of Wi-Fi probes accumulated by the area where they were installed.

Table A.1
The results collected from the field observation.

Indicators	Area 1	Area 2	Area 3	Area 4	Area 5
The total observed pedestrians	42	40	221	354	87
The total number of pedestrians who had recreational activities	16	13	39	78	6
The ratio of pedestrians that had recreational activities	38.1%	32.5%	17.6%	22.0%	6.9%

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