Evaluating Neighborhood Environment and Utilitarian Walking Behavior with Big Data: A Case Study in Tokyo Metropolitan Area

Hao Hou and Yuji Murayama

Introduction

Fast development in transport technology has brought great convenience to people's daily life, especially for those who live in highly urbanized areas. However, the convenience in daily life caused that a significant proportion of people all over the world adopted a physically inactive lifestyle (Van Dyck et al. 2013). Around 50% of the population in America were found to be physically inactive (Hallal et al. 2012) and the proportion of inactive adults in Australia even reached 57% (Wang et al. 2016). Besides the high proportion, the trend of an increase in the proportion of physically inactive people was also noticed. In Japan, the proportion of adults achieving 10,000 steps per day fell by 5% from 2000 to 2007 (Inoue et al. 2011). The evidence in China showed that the average physical activity level of Chinese adults decreased by more than 30% from 1999 to 2006 (Ng et al. 2009). Physical inactivity was found to be linked with higher risks of overweight and obesity. Besides, physical inactive lifestyles affect people's mental health as it can increase the mental pressure and cause depression (Wang et al. 2016). As a result, the promotion of physical activity is attracting high attention and becoming a health priority in recent years (Heath et al. 2012).

Among all the physical activities, walking is recognized as one of the most common, accessible, inexpensive forms of physical activity and is an important component of total physical activity in adult populations (Hallal et al. 2012). In this context, knowledge on how to promote people's daily walking behavior is critical. In recent years, a number of studies have revealed the relationships between

H. Hou (✉) · Y. Murayama
Division of Spatial Information Science, Graduate School of Life and Environmental Sciences, University of Tsukuba, 1-1-1Tennodai, Tsukuba, Ibaraki 305-8572, Japan
e-mail: houhao880828@gmail.com

neighborhood environment and walking behavior (Azmi et al. 2013; Eronen et al. 2014; Van Dyck et al. 2009). Generally, walking behavior can broadly be categorized into three types: recreational, occupational and utilitarian walking. Recreational and utilitarian walking behavior are frequently compared with neighborhood environment (Saelens and Handy 2008). Recreational walking behavior refers to those undertaken in someone's leisure time without a determined destination, such as taking a walk in a park, running along the track or walking a dog. On the other hand, utilitarian walking behavior always has a specific destination and the walking is regarded as mobile means similar to riding a bicycle, taking a bus or driving a car. Considering only the physical attributes, utilitarian walking behavior tends to have a stronger relationship with neighborhood environment compared to recreational walking behavior (Lee and Moudon 2006).

Studies on evaluating neighborhood environment started with the adoption of perceived data gaining from questionnaires. One of the most widely used questionnaires is the NEWS (Neighborhood Environment Walkability Survey) developed in 2002 (Saelens et al. 2003). The questionnaire-based data is easy to be analyzed but the collecting process is both time and money consuming. As a result, this approach is not applicable to studies carried out on a large scale and most of these studies concentrated on a community level (Azmi et al. 2013; Chen et al. 2013; Kamada et al. 2009; Kondo et al. 2009). In recent years, with the development of GIS (Geographical Information System) as well as the growing number of available spatial data, studies on neighborhood environment with objective data analyzed by GIS software is becoming popular (Hanibuchi et al. 2011; Lamíquiz et al. 2015; Leslie et al. 2007). The approach based on available spatial data and GIS software can reduce the cost of collecting data. Besides, GIS software provides the function to visualize and analyze the data from the spatial view, including the capacity of mapping, spatial analysis and modeling (Leslie et al. 2007). These advantages provide a possibility to evaluate neighborhood environment on a large scale (such as a municipality level) and compare the results with the spatial patterns of urban structure and the public transportation system.

However, the adoption of GIS and objective spatial data brings several challenges in data handling. First, spatial data from different sources may differ in format, coordinate system, the definition of attributes, resolution, scale, etc. All of these differences need to be unified according to the study area. The process of unification may require simulation of some mismatched or missing data. Second, huge data often includes plenty of information. However, a specific study only needs a small part of the whole data set. As a result, the extraction of useful information (known as "data mining") is a necessary step during the data handling and this step requires knowledge of the whole data structure. Third, analyzing big data requires great computing power. Computer and software may have limitations in the maximum amount of records and the maximum data size. In this case, the data need to be divided according to the limitation of computing power and processed separately. Although these challenges exist, using GIS and objective spatial data in neighborhood environmental studies is attractive as it provides different views and understanding in this field (McGinn et al. 2007).

The purpose of this study is to evaluate the neighborhood environment and utilitarian walking behavior in Tokyo Metropolitan Area and compare the results to check the relationships. Although plenty of studies on detecting relationships between neighborhood environment and walking activity existed, limited studies were carried out in a study area covering such a big metropolitan level scale (Sundquist et al. 2015). This study is able to provide the spatial patterns of both neighborhood environment and walking behavior which are important for urban planners and public transportation designers. The produced data in this study can also be related to other social-economic data for further studies.

Methodology

This study was separated into two parts: the evaluation of neighborhood environment and the evaluation of utilitarian walking behavior. For the evaluation of neighborhood environment, we used the location data of residential buildings from Zenrin© TOWN II digital map, the road network data from OpenStreetMap Project, the land use information and spatial distribution of public transportation facilities (including the locations of bus stop and railway stations) from National Land Numerical Information constructed by the Japanese government. For the evaluation of utilitarian walking behavior, we employed the People Flow Data of Tokyo in 2008 made by CSIS (Center for Spatial Information Science), University of Tokyo.

Study Area

The Tokyo metropolitan study area is composed of the city of Tokyo, the prefectures of Chiba, Kanagawa and Saitama, and the southern part of Ibaraki prefecture (Fig. 1). The study area was decided based on the available scale of the People Flow Data. This area is known as one of the largest metropolitan areas around the world. The population of this area reached 37.6 million in 2010 and parts of the Tokyo city had the highest population densities in the world (Bagan and Yamagata 2012). The Tokyo Metropolitan Area owned the world's most extensive urban rail network. According to the latest data from the government, the public transportation system served more than 900 million passengers in 2014 (Bureau of General Affairs, Tokyo Metropolitan Government 2014).

Measures of Neighborhood Environment

Five criteria were selected to evaluate the neighborhood environments including residential density, street connectivity, land use diversity, bus stop density and
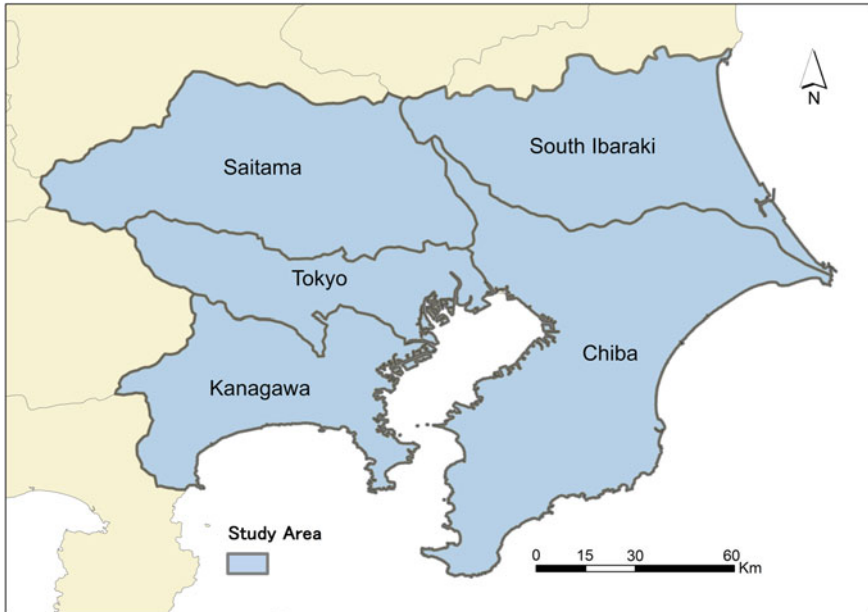
Fig. 1 Study area: Tokyo Metropolitan Area (TMA)

railway station accessibility. The first three criteria were widely used in the evaluation of neighborhood environment and walkability in the previous studies (Jun and Hur 2015; Lamíquiz and López-Domínguez 2015; Sundquist et al. 2011). The last two criteria, bus stop density and railway station accessibility, were included in this study since residents in TMA relied a lot on the public transportation in their daily lives. The neighborhood was defined as the area with a distance less than 1 km to the residence. The selection of 1 km radius buffer resulted from the evidence in previous study which showed that neighborhood environment attributes within 1 km home buffers were positively associated with moderate-vigorous physical activity in the buffer (Troped et al. 2010). Finally, through the Multi-criteria Evaluation approach, all the criteria were combined to calculate the index for evaluating neighborhood environment. The index was named "walkability", which was used to evaluate the extent to which the built environment was friendly to the presence of people's walking behavior.

Residential Density

Locations of residential buildings in TMA were derived from Zenrin© TOWN II digital maps. The first step was the combination of all the town maps. More than 200 layers were merged together with the function in the ArcGIS® software package, version 10.2. The next step was to extract residential buildings from all the
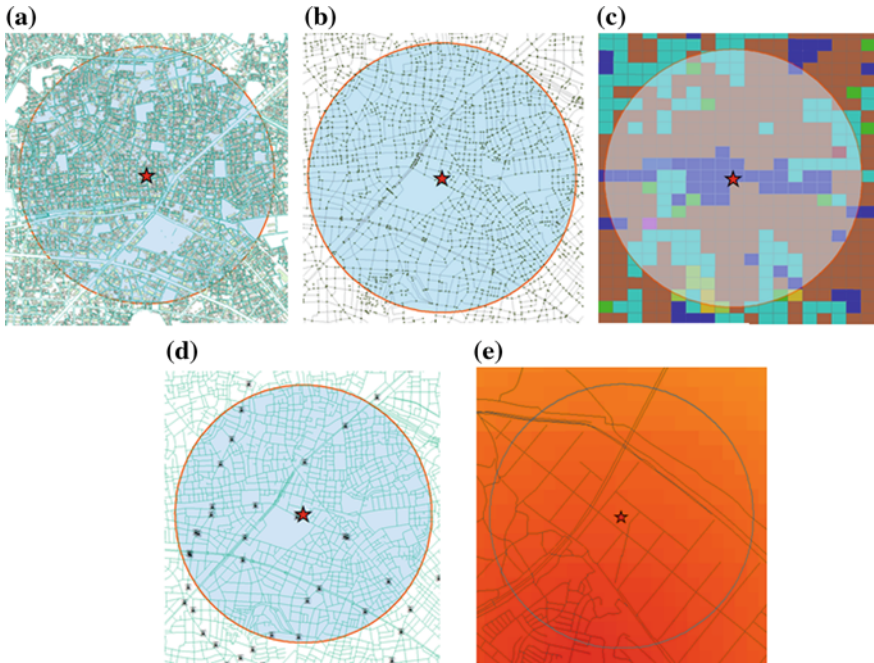
Fig. 2 Evaluation with 1-km buffer for (*left–right*): **a** residential density, **b** street connectivity, **c** land use diversity, **d** bus stop density and **e** railway station accessibility

buildings by the attribute of type. This step made the total number of features decreased from 16.4 million to 9.2 million. After this, a point-based resident's location layer obtained from the People Flow Data was added for creating the neighborhood buffers of each person. With overlay analysis, the count of residential buildings in each buffer was summarized and this value was made as the residential density of each residence (Fig. 2a).

Street Connectivity

In this study, the street connectivity was evaluated by the number of intersections within each neighborhood. Data from OpenStreetMap Project were utilized to get the road layer. Later, according to the description of the road categories, only the roads available for walking behavior were extracted. Next, the "network analysis" function, which is available in the ArcGIS® software package, version 10.2, was used to building road network and get intersections. Finally, the layer of neighborhood buffers created before were overlaid with the layer of intersections to get the count of intersections within each neighborhood as the value of street connectivity (Fig. 2b).

Land Use Diversity

The original data used for the measurement of land use diversity came from the 100 m × 100 m land use mesh data included in the National Land Numerical Information constructed by the Japanese government. The original data had a number of 12 land use categories. Later they were reclassified into five categories since the purpose of evaluating this factor was to detect potential destinations for people's daily walking behavior. The five categories included: single-family residential area, multifamily residential area, commercial area, public service area and green space. Land use diversity was calculated by the formula below and the value (d) represented the diversity of each person's neighborhood (Fig. 2c):

$$d = \mathbf{I} \frac{\sum k (\mathrm{p}_k \ln \mathrm{p}_k)}{\ln N}$$

where d is the diversity value; k is the category of land use; p is the proportion of each land use category; N is the number of land use categories. The equation results in between 0 and 1, with 0 representing a single type of all land use and 1, a developed area with all land use categories.

Bus Stop Density

The bus stop density value was defined as the count of bus stop in each neighborhood buffer (Fig. 2d). The original data recording the spatial location of bus stop were derived from the National Land Numerical Information. The number of bus stop in each resident's neighborhood indicated the scale of accessible areas reached by taking a bus. With a higher bus stop density, residents in the neighborhood intended to have a higher possibility to choose bus as the movement means. When people choose to go out by bus, the utilitarian walking behavior usually happens since they need to take a walk to reach the bus stops.

Railway Stations Accessibility

The railway station accessibility was evaluated through the Euclidean Distance from each residential point to the closest railway station. The raster layer with a cell size of 100 m was created and the value of each cell was the distance to the nearest railway station. The neighborhood buffers were later utilized to get the average value of distance in each neighborhood (Fig. 2e). As mentioned above, good access to the public transportation facilities can encourage the utilitarian walking behavior with the purpose of reaching those facilities.

Multi-criteria Evaluation Approach

After the evaluation of five criteria, equal weights were given to the value of each criterion to calculate the final walkability. The decision of weights was based on the previous study (Leslie et al. 2007). All the values were normalized to force the values to fall into 0 and 1. As a result, the final values of walkability ranged between 0 and 5. According to the values of walkability, the whole areas were categorized into five groups shown in Table 1.

Measures of Utilitarian Walking Behavior

In this study, the total utilitarian walking time per day was adopted as the value to present each person's level of utilitarian walking behavior. The data source for the measures was the People Flow Data. The People Flow Data is a data set processed for monitoring dynamic changes in daily people flow, which provides the individual locations in every minute within 24 h. The procedures of data processing included: (a) geocoding the first and last points of sub-trips to specify spatiotemporal locations, (b) calculating the shortest route between the two locations, and (c) interpolating minute-to-minute location information based on detailed network data. In this study, the People Flow Data of Tokyo in 2008 was used for the measurement and the total number of samples reached 576,806. Table 2 showed the structure of the People Flow Data. The critical fields used in this study are PID, LON, LAT, PURPOSE, and TCODE. TCODE helped to extract only the walking behavior. The spatial information of the walking activities was recorded by LON and LAT. PURPOSE was for extracting only the utilitarian walking from all the walking behavior. Table 3 shows all the purpose of walking behavior. In this study, the authors tried to ignore those occasional walking behavior and to focus on only the utilitarian walking behavior happened almost every day. In this context, only the first four (code 1–4) categories were considered as the utilitarian walking behavior. After the extraction, the records were summarized based on PID to link the walking behavior with the neighborhood environment.

Table 1 Area separation based on walkability

Walkability (0 ∼ 5)	Category
0–1	Low walkable area
1–2	Medium low walkable area
2–3	Medium walkable area
3–4	Medium high walkable area
4–5	High walkable area

Table 2 Structure of people flow data

Field ID	Field name	Description
1	PID	Unique person ID
2	TNO	Trip number
3	SNO	Sub trip number
4	LON	Longitude position
5	LAT	Latitude position
6	GENDER	Gender
7	AGE	Age group
8	ZCODE	Current location by zone code
9	OCCUP	Person occupation
10	PURPOSE	Purpose to trip
11	MAGFAC	Adjustment factor
12	MAGFAC2	Adjustment factor
13	TCODE	Mode of transportation

Table 3 Purpose code in people flow data

Code	Value	Code	Value
1	To office	9	To send/pick up activity
2	To school	10	For selling and buying
3	To home	11	For appointment
4	To shopping place	12	To/for work (fixing and repairing)
5	For dinner/short recreation	13	To agriculture/forestry/fishery work
6	For sightseeing and leisure	14	Other business purpose
7	For medical treatment	99	Others
8	For other private purpose		

Visualization with Standard 1 Km × 1 Km Mesh

After the evaluation process, all the results were summarized by the standard 1 km × 1 km grid net established by the Geospatial Information Authority of Japan. The value of each grid was determined by the average value of all the residential points that fell into this grid. There were two objectives for this approach: creating standard data and visualization. Data summarized by the standard 1 km × 1 km grid net is applicable for comparative studies with other social and economic data published by the Japanese government which utilized the same unit. Instead of point-based results, the grid-based results are clearer for visualization and easier for detecting the spatial patterns of the results.

Results

Evaluation Results of Five Criteria

Figure 3 showed the evaluation results for the five criteria separately. Results of residential density (Fig. 3a) showed that except for the Chu'o ward which was located in the central of TMA, the residents in the other 22 special wards of Tokyo all had a high residential density. Besides these areas, the high residential area appeared along the railway lines revealed a common pattern that people intended to live in places with a good accessibility to the railway stations. The low value appeared in both the central area of Tokyo and the rural areas of the metropolitan area. Low residential density in the central area resulted from that most of the buildings there were commercial land use. On the other hand, rural areas had a low residential density because of the low population density there. Street connectivity showed a similar spatial pattern with the residential density (Fig. 3b) that the highest value appeared in the urban areas with a short distance to the urban core while the lowest values appeared in the rural areas far from the urban core. The spatial patterns of these two criteria can be understood from the perspective of urban structure. The suburban areas close to the city center were usually designed as the residential areas with a high density of residential buildings and standard road networks. The result of land use diversity (Fig. 3c) had a slim difference compared with the first two criteria. Although the lowest value was still assigned to the rural areas, the highest value appeared both in the urban core and the urban areas relatively close to the urban core. The diverse land use in the central area resulted from the need to serve the big flowing population passed there every day. What's more, some suburban areas had the same low values as rural areas. This indicates that some of the residential areas in Tokyo might be in a lack of enough facilities for daily life in the neighborhood context. Results of the bus stop density (Fig. 3d) and the railway station accessibility (Fig. 3e) showed similar spatial patterns. The areas within the urban boundary had higher values than those rural areas. This proved that the Tokyo city had a complete public transportation system to serve all the citizens regardless of the distance to the city center while in rural areas only residents living in places close to the railway lines enjoyed good accessibility to the public transportation facilities.

Evaluation Results of Neighborhood Environment (Walkability)

The five criteria were merged together with the equal weight and the result was shown in Fig. 4. All the areas were categorized into five groups (Table 1) by the value of their walkability. Most of the high walkable areas concentrated in the 23 special wards of Tokyo except the Chu'o ward. Residents here enjoyed a good
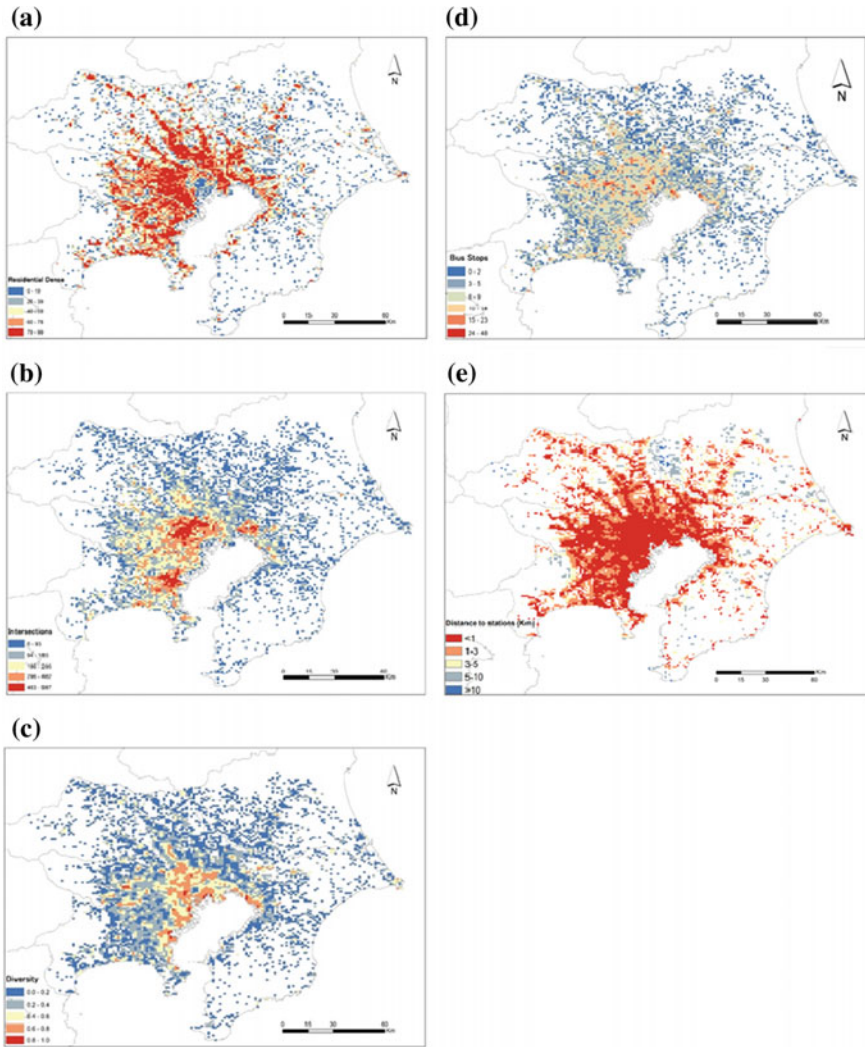
Fig. 3 Grid-based maps of **a** residential density; **b** street connectivity; **c** land use diversity; **d** bus stop density; **e** railway station accessibility

accessibility to public transportation facilities which encourages them to have a walk to reach stations. The high diversity of land use here provided plenty of potential destinations for residents to walk to within the neighborhood scale. The complex road network here reduced the potential to move by a private car. The medium walkable area appeared along the railway lines as well as the municipal lines between Special wards of Tokyo and other prefectures. Residents here owned a good accessibility to the public transportation facilities and the residential buildings. However, the diversity of land use was relatively low compared to the

high walkable areas, which indicated a low potential for daily walking behavior within the neighborhood. Low walkable areas scattered in the rural areas with the longest distance to the city center compared to the other categories. Residents here suffered a bad accessibility to the public transportation facilities, and it led to a high potential to use a private car for daily movement. The low residential density and land use diversity here reduced the chance for residents to reach a destination by walking since the potential destinations were far from their living places. The walkability map was related to the urban structure from the spatial perspective that except for the central business district (the Chu'o ward), the walkability decreased when the distance to the urban core increased.

Evaluation Results of Utilitarian Walking Behavior

Results of the utilitarian walking time (Fig. 5) showed that rural residents' utilitarian walking time per day were less than the time of people who live in the urban core and suburban areas. Most of the residents in rural areas had a utilitarian walking time of fewer than 10 min per day. While residents in the suburban areas close to the boundary of each prefecture usually walked more than 10 min per day for the utilitarian purposes. But most of them didn't reach the 30 min utilitarian walking time in one day. People living in the urban areas close to the city center had
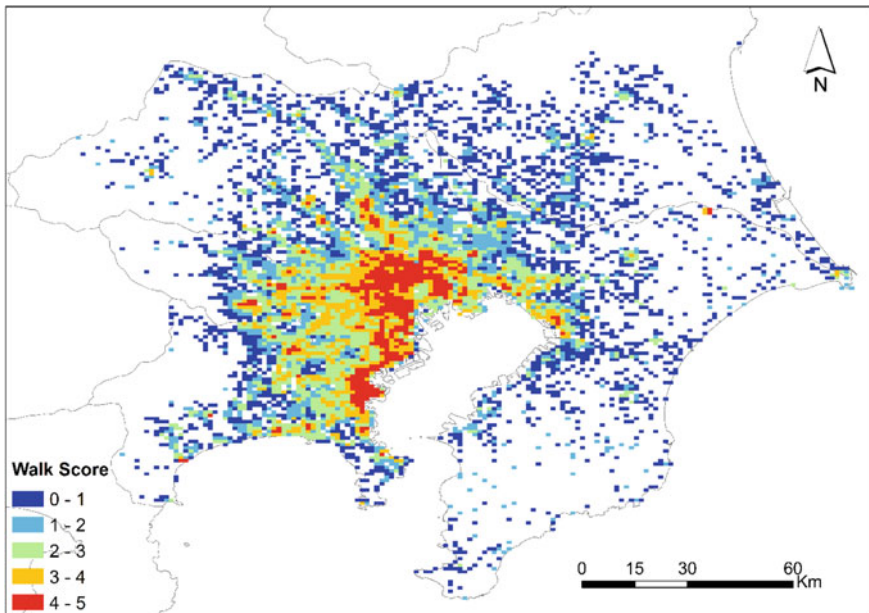

Fig. 4 Grid-based map of walkability in TMA

a higher average utilitarian walking time per day. This result kept a consistence with the findings from the evaluation of walkability. The majority of the residents in this area had a utilitarian walking time reaching the level of 20–30 min. Residents with more than 30 min utilitarian walking time per day could be easily found in this area. The utilitarian walking behavior of residents in the Chu'o ward was slimly mismatched with the findings of walkability evaluation. Residents here had a similar level of daily utilitarian walking behavior with the residents living close to the city center (mostly in 20–30 min level and 30–40 min level) although the walkability in Chu'o ward was less than the surrounding areas.

Comparison Between Walkability and Utilitarian Walking Time

By comparing Figs. 4 and 5, similar spatial patterns can be detected that residents in the rural areas have low walkability in the neighborhood and low utilitarian walking time. On the other hand, residents in the urban areas, especially areas close to the city center, enjoyed high walkability and had more utilitarian walking time per day. With the statistics shown in Table 4, the consistence between the evaluation results of walkability and utilitarian walking time was clearer. Although the maximum utilitarian walking time shown in the second column did not match the walkability
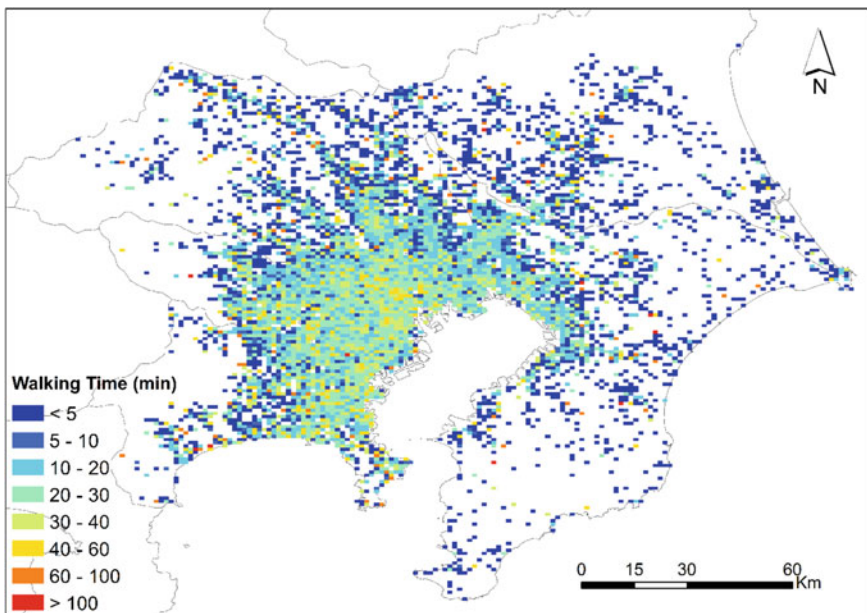

Fig. 5 Grid-based map of utilitarian walking time in TMA

Table 4 Comparison of walkability and utilitarian walking time

Walkability	Max UWT (min)	Mean UWT (min)	Count of grids	Proportion (%)
0–1	152	9.6	1288	22.38
1–2	144	11.7	1560	27.11
2–3	182	17.1	1410	24.50
3–4	62	22.2	961	16.70
4–5	82	24.9	535	9.30

value, the mean utilitarian walking time perfectly matched the walkability. Residents who live in the areas assigned with a low walkability value do have lower mean utilitarian walking time every day. Count of grids showed the proportion of each category valued by walkability in TMA. The table showed that the medium low walkable area (value: 1–2) covered the largest area of TMA, followed by the medium walkable area (value: 2–3) and the low walkable area (value: 0–1). The left two categories, the medium high and the high walkable areas, only covered 26% of the whole study area.

Discussion

The evaluation of neighborhood environment for walking is popular in recent years as people pay more attention to personal health. Many studies tried to evaluate neighborhood environment or walkability with both objective and self-reported data. However, because of the differences in the study area and personal attributes, there is no standard approach for all the analysis. The differences mainly appear in the selection of criteria considering the purpose of each study. For example, one study about detecting the effect of neighborhood environment on walking for transportation adopted street connectivity, land use mix and residential density as the criteria for evaluation (Turrell et al. 2013). Another study aiming at finding the association between destination and route attributes with walking chose sidewalks, street connectivity, aesthetics, traffic and safety as the criteria (Sugiyama et al. 2012). As a result, when doing researches on this field, there is a need to consider about the selection of which criteria should be included. Studies of neighborhood environment carried out in America or Europe usually don't use public transportation factors (Sundquist et al. 2011; Troped et al. 2010) while researchers doing studies in Japan need to consider this factor as public transportation system is widely and frequently used here.

The main purpose of this study is to detect the relationship between neighborhood environment and utilitarian walking behavior. Although more detailed and deeper statistical analysis was needed, the results reflected that people living in high walkable areas really had more average utilitarian walking time. Studies focusing on utilitarian walking behavior were still limited in this field. Previous studies only proved that moving to a more walkable neighborhood was associated with an

increase in utilitarian walking time (Hirsch et al. 2014). And utilitarian walking behavior had a positive association with the local accessibility to amenities (Wasfi et al. 2015). Since utilitarian walking behavior is the most common walking behavior happened almost every day, more studies are needed to detect the potential ways to improve the level of this walking behavior. Besides the findings of relationship, this study also released the maps of five neighborhood attributes, walkability, and utilitarian walking time. All the maps showed the spatial patterns similar to the urban structure. Previous studies mostly concentrated on a micro scale, but the findings here showed a possibility of comparing the neighborhood environment in the whole urban structure.

The GIS-based objective measurement for neighborhood environment walkability seems to be more reliable than the perceived subjective measurements if the accuracy of the spatial data is acceptable because participants' perception of their neighborhood may vary even if they live in the same place. With the increasing computing capabilities, the GIS-based objective measurement provides a considerable opportunity to develop more accurate measures of the neighborhood environment. This study showed one basic way of interpreting related spatial data together for the evaluation and it also proved that GIS is suitable for handling big spatial data. With the technical developments in computer science and the increase of available open data sources, the GIS-based objective measurement is supposed to behave better in the future.

There are several limitations to this study. First is the missing of some potential variables that may improve the results. Although the consistence can be found by comparing the evaluation results of walkability and utilitarian walking time, some areas such as the Chu'o ward showed mismatched patterns. Further study is needed for adding new variables to check and improve the results. Second is the use of self-reported data for the evaluation of utilitarian walking time. The People Flow Data is excellent since it covers the whole Tokyo Metropolitan Area with a big number of sample. However, the original data came from the self-reported questionnaires and this kind of data is hard to remove the influence of subjective bias to recall and response (Kamada et al. 2009). Third is the ignorance of personal attributes. This study utilized the whole data set without extraction of any specific groups of people. However, previous studies have proved that people's walking behavior were related to personal attributes such as age (Hanibuchi et al. 2011), gender (Van Dyck et al. 2013), income (Owen et al. 2007), driving status (Kamada et al. 2009), etc. In order to increase the accuracy of the results, the extraction of different groups was considered in the future study.

Conclusion

The results showed that residents in urban areas with a good accessibility to the city center had the highest potential for daily utilitarian walking behavior, followed by the residents in the urban core and rural areas. The spatial patterns of the result had

a consistence with the result of personal utilitarian walking time derived from the People Flow Data. This consistence proved that residential density, street connectivity, land use diversity, bus stop density, railway station accessibility are necessary factors for evaluating neighborhood environment in TMA. The evaluation of neighborhood environment reflected the reality and the results can be utilized by both urban planners and transportation network designers for building a more walkable city. Future studies are encouraged on deeper statistical analysis of the relationships between neighborhood environment and utilitarian walking time to increase the confidence of the findings.

This study employed an 1-km radius buffer to calculate each criterion to evaluate neighborhood environment for daily walking behavior and basic grids for visualizing the spatial patterns of the evaluation results. The outcomes of this study supported that the handling of spatial data about neighborhood environment with certain buffers was reasonable. The approach of processing objective GIS data and subjective questionnaire-based data in this study was worth to be applied to other metropolitan areas.

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