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Examining non-linear associations between built environments around workplace and adults' walking behaviour in Shanghai, China

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ABSTRACT

Considering that most working adults spend nearly half their waking time at work, creating a supportive built environment around workplaces could be a feasible approach to maintain adequate levels of physical activity. However, the extent to which the built environment around workplaces influences walking behaviors in working adults remains unclear. Using survey data of 1009 full-time employees in Shanghai, China, this study assessed the nonlinear relationships between the built environment characteristics around workplaces and three domains of walking behaviors (commuting, utilitarian, and recreational walking). Using gradient boosting decision trees, our results showed that the built environment around workplaces is crucial for higher levels of walking behaviors, but built environment features tended to have distinctive associations with different domains of walking behaviors. Specifically, the number of physical activity facilities was positively associated with all three domains of walking behaviors, while a high floor area ratio was negatively associated with different domains of walking behaviors to some extent. Furthermore, several built environment characteristics, such as land use entropy, street view greenery, distance from home to the city center, and distance between the city center and workplaces had distinctive associations with different domains of walking behaviors. The findings of this study could provide nuanced guidance for creating pedestrian-friendly environments around workplaces to promote walking behaviors and overall physical activity levels in the working population.

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1. Introduction

Walking is the most common form of physical activity, which does not require a specific skill or equipment (Kerr et al., 2016). While contributing to numerous health outcomes (e.g., lower risk of cardiovascular diseases, adiposity, and type II diabetes) (Lee et al., 2012; Vogel et al., 2009), due to the increasing number of sedentary occupations and the widespread use of motorized transport, the average individual's level of physical activity, including walking, has declined significantly in the past three decades in China. On average, the weekly physical activity level of adults has decreased by 30.9% from 1991 to 2011 (Ng et al., 2014).

To counteract the declining levels of walking, researchers in urban planning, transportation, and public health have recognized the importance of an active living environment (i.e., a well-designed built environment) that can help people incorporate physical activities (e.g., walking and cycling) into their daily routines (Adlakha et al., 2015; He et al., 2021; Van Dyck et al., 2013). There is increasing evidence highlighting the importance of some built environment elements, such as the presence of public transportation facilities (Gao et al., 2019), accessible destinations (Sallis, Owen, & Fisher, 2015), dense and mixed-used urban developments (Forsyth et al., 2007), well-connected street networks (Koohsari et al., 2014), and pleasant streets (Lu, Sarkar, & Xiao, 2018).

In the past two decades, focusing on residential neighborhood environments, numerous studies have verified associations between the built environment and people's daily walking behaviors (Wang et al., 2021; Zhao and Wan, 2020). Most studies have revealed that individuals who live in more populated residential neighborhoods with higher levels of land use diversity, greater transit accessibility, and more pedestrian facilities tend to walk more (Kang et al., 2017; Sun et al., 2020; Yang et al., 2019). Such findings have been verified in various geographical locations and cultural contexts (Sallis, Owen, & Fisher, 2015).

Despite many efforts, the current understanding of the association between the built environment and walking behaviors remains insufficient. First, with a few exceptions (Wang et al., 2021), previous studies have largely failed to distinguish different domains of walking behaviors (e.g., commuting, utilitarian, and recreational walking), and it is possible that built environment features may have distinctive effects on the different domains of walking behaviors (Zhao & Wan, 2020). For example, the proximity of pedestrian destinations (i.e., accessible stores) may stimulate utilitarian walking but not recreational walking. Second, the association between the built environment and walking behaviors around workplaces is largely understudied. It is often assumed that all walking behaviors are conducted within residential neighborhoods, ignoring the fact that walking behaviors may be conducted in multiple places (Adlakha et al., 2015; Schwartz et al., 2009). Focusing on residential neighborhoods may increase the risk of bias in the association between the built environment and walking behaviors. Third, most studies have focused on linear associations between the built environment and walking behaviors; however, the attributes of the built environment may not exert consistently positive or negative effects on walking behaviors. but there are possible complex non-linear associations (Van Wee & Handy, 2016). In addition, the effects may become saturated and even contrary once they have exceeded a specific cut-off point (Cheng et al., 2020). Thus, such a simplification of the linear association lacks theoretical foundation and may further lead to an estimation bias (Yang et al., 2021a). For instance, although there is a known positive association between population density and walking (Forsyth et al., 2007), an inverted U-shaped relationship has been reported in a high-density urban context (Lu et al., 2019).

To address the identified research gaps, this study aims to assess non-linear relationships between the built environment around people's workplaces and the different domains of walking (i.e., commuting, utilitarian, and recreational walking) in Shanghai, China. This is the first study to investigate how the built environment around workplaces correlates with different domains of walking.

2. Literature review

2.1. Built environment and walking

Numerous studies have paid attention to the role of the built environment to explain people's walking behaviors (Sallis, Owen, & Fisher, 2015). By focusing on the residential environment (Gehrke & Welch, 2017), studies have illustrated that dense, compact, and mix-use residential neighborhoods are more likely to encourage walking trips (Cerin et al., 2017; Sun et al., 2017). The underlying explanation is that higher urban densities accommodate more facilities, and mixed land use allows residents to arrive at different types of destinations more easily (Kamruzzaman et al., 2016). Greater accessibility to pedestrian destinations and well-connected street networks also improve the proximity of destinations with alternative routes (Jack & McCormack, 2014).

Considering the complexity of walking behaviors, several studies have highlighted that walking trips can be broadly distinguished into transportation and recreational walking based on the purpose of the walking activity (Mirzaei et al., 2018; Gao et al., 2019). Transport-related trips can be further classified into commuting and utilitarian walking (Chan, Schwanen, & Banister, 2019). Theoretically, due to the hedonic nature of recreational walking, individuals may not have an incentive to minimize the time and expense associated with this activity (Mirzaei et al., 2018). In contrast, travel time, monetary expenditures, and psychological factors may constrain transportation walking in terms of frequency and duration. For instance, commuting walking generally lacks flexibility and discretion, and the determinants of commuting walking are likely different from those of utilitarian walking (Zhao & Wan, 2020). It comes as no surprise that associations between the built environment and walking behaviors are inconsistent across different domains (Mirzaei et al., 2018).

Recent findings have shown that some residential environment attributes have distinctive associations with different domains of walking (Zhao & Wan, 2020; Kang et al., 2017). Population density and street connectivity are associated with all domains of walking (Ussery et al., 2018); however, other built environment characteristics are associated with some but not all walking domains (Koohsari et al., 2014; Wang et al., 2021). For instance, a study in Beijing, China revealed that diversity in land use encourages recreational walking, but it is not correlated with commuting or utilitarian walking (Zhao & Wan, 2020). As comparative analyses of how the built environment influences various domains of walking remain limited, more related studies are warranted (Chan, Schwanen, & Banister, 2019).

2.2. *Workplace neighborhood environment and walking*

Most prior studies have implicitly assumed that all walking trips occur within a residential neighborhood (Adams, Bull, & Foster, 2016); however, such an assumption ignores the fact that individuals are exposed to other environments throughout the day (Liu et al., 2020; Lin et al., 2020). Thus, studies that neglect environments other than residential areas may misevaluate the association between the built environment and walking (Marquet et al., 2020). Given that most employees spend half their day at work (Hipp et al., 2017), workplace neighborhoods that encourage walking behaviors are crucial to compensate for the time spent doing sedentary work (Van Uffelen et al., 2010). Although employees spend time at their workplace for work rather than leisure purposes, they have ample opportunity to be physically active, such as active travelling (e.g., cycling to work) and participating in leisure activities during work breaks and before and after work (Ekelund et al., 2016).

Nonetheless, insufficient attention has been paid to investigating how the built environment around the workplace affects employees' walking behaviors (Adlakha et al., 2015). Only a few studies have focused on commuting walking and highlighted that the built environment attributes may have distinctive associations with commuting walking compared to those of residential areas (Adams et al., 2016; Carlson et al., 2018). Some utilitarian walking trips conducted around workplaces may also depend on different incentives from walking trips in residential neighborhoods (Marquet et al., 2020; Vale & Pereira, 2016). For instance, individuals living in suburban areas may not find it convenient to run errands and go shopping (Chaix et al., 2017), while pedestrian-friendly workplaces in city centers may satisfy their needs and encourage utilitarian walking.

2.3. *Non-linear association between the built environment and walking*

It seems logical to presume a linear relationship between the built environment and walking (Zhao and Wan, 2020); however, an increasing number of studies have questioned this restrictive assumption by reporting alternative non-linear associations (Lu et al., 2019; Cerin et al., 2017). The following mechanisms have been proposed to explain complex non-linear associations between the built environment and walking (Cheng et al., 2020). First, the utilitarian nature of walking behavior encourages individuals to maintain a certain number of daily walking trips, regardless of their immediate environment (Mokhtarian & Salomon, 2001; Van Wee & Handy, 2016). Second, it would be unrealistic to assume that the associations between elements of the built environment will continue to increase as walking levels increase (Yang et al., 2021b). For instance, people might enjoy walking if the trips are not too long, but after a certain distance the positive utility diminishes and becomes negative (disutility). Thus, the utility value of walking becomes saturated when the amount of walking exceeds a certain threshold level (Cheng et al., 2020).

Christiansen et al. (2016) found a curvilinear relationship between transportation walking and residential density, greenery, and street connectivity. Lu et al. (2019) also reported that population density is nonlinearly correlated with transportation walking among youth in Hong Kong. By using machine learning models, non-linear associations between the built environment and transport-related outcomes have been identified (Cheng et al., 2020; Yang et al., 2021b). Specifically, Yang et al. (2021b) reported that street view greenery is positively associated with walking propensity within a certain range. Cheng et al. (2020) revealed that population density and mixed land use only increases walking at certain levels. Furthermore, extremely densified environments and excessively mixed land use may lead to a decline in walking activities. These conclusions question the validity of widely presumed linear associations and suggest that the effects of elements in the built environment may be effective only within a certain range (Wu et al., 2019).

3. Materials and method

3.1. *Study area and sample*

Shanghai is one of the most densely populated cities in China, with an average population density of 3814 people per square kilometer in its urban areas (Shanghai Statistical Yearbook Statistics, 2019). The metropolis has experienced rapid urban sprawl in recent decades, while most job opportunities are still concentrated within the area of the middle ring road. Consequently, the average commuting time for employees has increased from 41 min in 2004 to 43 min in 2011[1]. Most employees commute an average distance of 8.9 km between their homes and their workplaces (Sun, Ermagun, & Dan, 2017).

This study is based on survey data collected by the East China Normal University between September and December 2018. The data collection was based on the following procedure. Initially, 13 of Shanghai's highly built-up districts (excluding Jinshan, Fengxian, and Chongming) were selected. Next, to ensure the representativeness of the sample, multiple stages of stratified proportional sampling were adopted. After randomly selecting 30 primary sampling units (i.e., *jie dao* or town) in different districts, 1–2 housing estates (*xiao qu*) were randomly selected in each primary unit. In total, 38 housing estates were sampled. Lastly, 35 households were randomly selected with an equal number of samples in each housing estate. Research assistants approached the sampled households. If a member of the household was not available in the dwelling, the research assistant paid another visit. If a member of the household was absent

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[1] The fourth comprehensive traffic survey of Shanghai http://sh.eastday.com/chztl/4thjtsurvey/.

again or refused an interview, the next-door neighbor was selected. The head of the household or spouse, aged 18–60, was invited for a structured face-to-face interview.

The survey questionnaire included questions concerning the respondent's demographics, socioeconomic characteristics, daily behaviors, lifestyles, and job-related information. In total, 1127 respondents were invited to participate; among them, 1009 individuals who were full-time employees completed all the questions (Fig. 1). Based on the respondents' residential and workplace information, workplace locations were geocoded to collect data on the surrounding built environment. Consistent with other surveys carried out in Shanghai, most job positions were concentrated in the central business district (Sun, Ermagun, & Dan, 2017), and workplaces were distributed across all districts except in the Chongming district.

3.2. *Walking time as an outcome variable*

3.2.1. *Commuting walking*

Respondents reported detailed information on their last commuting trip from home to work, including transportation modes (i.e., car, walking, cycling, motorbike, metro, or bus) and the duration of the corresponding trip. They also reported the number of days they worked per week. If a respondent used multiple transportation modes for their commuting trips, they were requested to provide information on each mode and its duration. Multi-modal commuters using private cars were regarded as passive commuters; as private cars were the main mode of transport for these trips, the walking part of their commute was disregarded. By contrast, the walking time of commuters traveling to work by public transport were recorded. The weekly commuting walking time was calculated by multiplying the duration of walking in a single commuting trip and the number of working days per week. Given that commuting involves a round trip in daily life, the calculated time was doubled.

3.2.2. *Utilitarian walking*

Utilitarian walking includes walking for non-commuting travel purposes to satisfy daily needs (e.g., shopping, visiting friends, and running errands) (Zhao & Wan, 2020). Respondents self-reported the number of days and the duration of their daily utilitarian walking within the neighborhood of their workplace. By multiplying the frequency and daily duration over the preceding seven days for each respondent, the weekly utilitarian walking time within the workplace neighborhood was calculated.

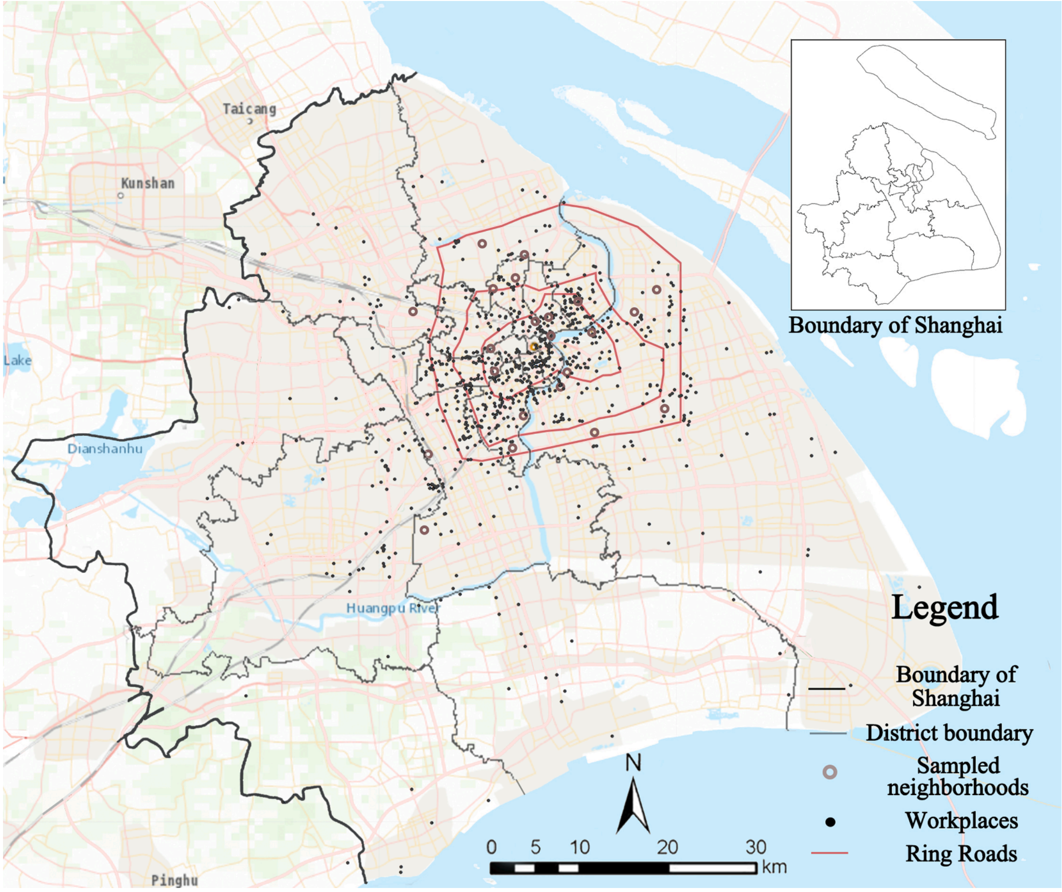

Fig 1. The distribution of the sampled neighborhoods and workplaces in Shanghai (N = 1009).

3.2.3. Recreational walking

In terms of recreational walking, respondents reported the number of days and daily duration over the preceding seven days that they engaged in recreational walking (i.e., strolling, jogging, and other walking behaviors) within the neighborhood of their workplace. Consequently, total weekly recreational walking time in minutes that occurred in the vicinity of workplaces were calculated per respondent based on frequency and duration.

3.3. Independent variables

3.3.1. Built environment variables

In this study, the built environment around workplaces was defined within a radius (circular buffer) of 1000 m from the location of an individual's workplace (Liu et al., 2020). To capture how people perceive their built environment, we employed street view data based on Baidu Maps (Ye et al., 2019). To collect street greenery features per workplace neighborhood, sampling points were created every 30 m using street networks based on Open Street Map data for 2018 (https://www.openstreetmap.org/). Streetscape images with a dimension of 1024 × 1024 pixels in the four cardinal directions of each sampling point were retrieved through the application programing interface (API) of Baidu Maps. Points that did not contain any image were removed. Then, deep learning was used to determine the amount of greenery per image. The pyramid scene parsing network (PSPNet) was trained based on Cityscape data (https://www.cityscapes-dataset.com) (Cordts et al., 2016). The greenery level of each sampling point refers to the average score of four images. Using all the points per workplace neighborhood, we determined the overall average street greenery level of workplace neighborhoods.

Several walkability-related metrics were important to promote walking behaviors, such as street connectivity, urban density, and land use mix (Wang et al., 2021). Specifically, street connectivity was defined as the number of road intersections within the buffer (Yang et al., 2021a). The building dataset was acquired from Gaode Map, which contained detailed information on building space coordinates, footprints, and the number of floors in a building. We measured floor area ratio (FAR) as the ratio of the total floor area of all buildings to the area of the circular buffer. Point of interest (POI) data were adopted to measure neighborhood land use mix by means of the Shannon entropy index (Yue et al., 2017). We used 15 different POI categories (e.g., retail and wholesale and catering transportation facility) to determine land use mix operationalized as the Shannon index.

The Euclidean distance between a respondent's home to the workplace, as well as the distance from the city center (*lu jia zui*) to workplace were calculated. We also identified the number of facilities and parks within neighborhoods respectively, in which people could perform physical activities per neighborhood (Liu et al., 2020). Using Baidu data, whether a metro station existed within 1000 m of workplaces was also calculated.

3.3.2. Individual-level covariates

Informed by previous research (Cheng et al., 2020; Zhao & Wan, 2020), we adjusted for the following individual-level covariates: female (female = 1, male = 0), age (in years), education level (middle school or below, high school, and college and above), *hukou* status (the household registration system in China; Shanghai *hukou* = 1, others = 0), marital status (married = 1, not married = 0), and annual household income (<100,000 CNY, 100,000–200,000 CNY, and >200,000 CNY). Given that health conditions influence the motivation for walking (Kroesen & De Vos, 2020), self-reported physical health was measured on a five-point Likert scale, and a higher score represented better self-reported health. Employment duration in the current job (in years) was also included.

3.4. Method

We used the gradient boosting decision tree (GBDT) (see Ding et al., 2018) machine learning algorithm to investigate non-linear relationships between the built environment around workplaces and the three types of walking. The training sample included the duration of the different types of walking, attributes of the built environment, and individual-level variables. Tree-based algorithms tend to have good predictive accuracy and allow us to evaluate the shapes of the associations between independent and dependent variables (Hagenauer & Helbich, 2017; Ding et al., 2018). Recent applications include the assessment of travel distance and transport carbon emissions (Wu et al., 2019). Briefly, GBDT evaluates the residuals between the calculated and target values using a gradient boosting algorithm. Next, the loss function of the current learner is minimized, and the ultimate residuals are iterated to obtain the final prediction close to zero, by adding up the results of all the trees to obtain the conclusive prediction (for details see Ding et al., 2018).

GBDT is superior to conventional regression models in the following ways (Wu et al., 2019). First, as GBDT is based on a combination of multiple learners, it avoids poor predictions that result from the limited capability of a single learner (Friedman, 2001). Second, unlike traditional linear regression, GBDT does not make any assumptions on the linearity of the associations and is less prone to multicollinearity among the covariates. Third, GBDT is flexible in that it can handle different types of data simultaneously and can cope with outliers and missing values. Fourth, GBDT provides the single and cumulative relative importance of different built environmental variables.

Studies have shown that the greater the number of trees, the deeper the depth of interaction, and the lower the learning rate, the better the fit; however, too many trees and a learning rate that is too slow may prolong the learning time and cause overfitting (Schonlau, 2005). In this study the interaction depth was set between 0 and 49 with a learning rate of 0.001 (Breiman, 2001). Per iteration, the model was fitted using four different subsets (80% of the data) and validated by the remaining subset (20% of the data). Different parameter combinations, together with a different number of trees (from 500 to 5,000 with an interval of 500), were tested, and the root mean squared error (RMSE) based on fivefold cross-validation assessed the model fit. The model with the lowest RMSE was used. Partial dependence plots were used to assess the directions and shape of the associations between walking time and the attributes of the built environment. The analysis was conducted in R version 3.6.3 through the "gbm" package (Ridgeway, 2007).

As a benchmark, we also compared the GBDT results with those of a conventional linear regression. Given that adding one independent variable could improve the regression's goodness of fit, we interpreted the proportion of the improvement in the overall goodness of fit (%R^2) as a measure of relative importance (Cheng et al., 2020).

4. Results

4.1. Descriptive statistics

Table 1 shows the descriptive statistics of the variables. Among the different domains of walking, commuting walking measures at the highest level with 124.99 min (standard deviation (SD) ± 130.03) over the preceding seven days, followed by utilitarian walking and recreational walking with average times of 51.02 min (SD ± 204.45) and 36.14 min (SD ± 96.76), respectively. Notably, the SD of walking time is high, as some respondents reported very few walking behaviors around their workplaces. The mean age of the respondents is 39.54 years (SD ± 10.17), and more than half of the respondents are female. Approximately 90% of the respondents have attended high school or had higher education level.

To ensure the representativeness of the sampled participants, we compare their characteristics with general population in Shanghai using census data in 2018 (Shanghai Municipal Statistics Bureau, 2019). The results confirm that the key demographic and socioeconomic characteristics of the respondents (e.g., age, gender, and household income) are similar to those of Shanghai's general population.

Table 2 summarizes the built environment variables. The average road intersection number is 59.76. The floor area ratio and street view greenery are 0.22 and 0.17, respectively. The numbers of physical activity facilities and parks are 160.02 and 1.91, respectively, and the average land use entropy is 2.16. Approximately 63% of workplace neighborhoods have access to at least one metro station within 1000 m.

4.2. Relative importance of explanatory variables

Table S1 in supplementary materials summarizes the optimal parameter settings for different walking outcomes. Specifically, both learning rate and number of trees reveal the training performance, and the RMSE shows the goodness of fit between the predicted and true values. The pseudo R^2s for three model are 0.763, 0.646, and 0.566, respectively. The selected parameters of the different models are shown in Appendix A1. These results suggest that the predictive performance of the GBDT model is sound, which is consistent with previous studies (Ding et al., 2018; Wu et al., 2019).

Table 3 shows the relative importance of each independent variable in explaining the three domains of walking. In terms of commuting walking, the characteristics of the built environment contribute to 75.6% of the total variances. Specifically, distance from home to the workplace is the most important covariate, with a contribution of 16.1%. The number of physical activity facilities, street view greenery, floor area ratio, road intersections, distance from the city center to workplaces, and land-use mix contribute approximately 8–10%.

Built environment attributes account for 86.2% of the variances in utilitarian walking. Distance from home to the workplace

Table 1
Descriptive statistics of the individual-level attributes (N = 1009).

Variables	Proportion/Mean (SD)
Dependent variables	
Recreational walking (min/week)	36.14 (96.76)
Commuting walking (min/week)	124.99 (130.03)
Utilitarian walking (min/week)	51.02 (204.45)
Independent variables	
Female (%) (Yes = 1)	54.02
Age (years)	39.54 (10.17)
Household annual income (%)	
Low (<100,000 CNY)	29.32
Mid (100,000–200,000 CNY)	35.18
High (>200,000 CNY)	33.50
Education level (%)	
Middle school or below	12.09
High school	50.45
College and above	37.46
Employment duration in the current job (years)	10.58 (9.81)
Shanghai hukou (%) (Yes = 1)	77.01
Married (%) (Yes = 1)	76.80
Self-rated overall health	4.08 (0.65)

Table 2
Descriptive statistics of the built environment attributes around workplace neighbourhoods (N = 1009).

Variables	Proportion/Mean (SD)
Street view greenery	0.17 (0.23)
Number of road intersections	59.76 (33.83)
Floor area ratio	1.46 (0.73)
Land use entropy	2.16 (0.30)
Number of physical activity facilities	160.02 (257.95)
Number of parks	1.93 (1.91)
Metro station within 1000 m (%)	63.31
Distance from the city center to workplaces (km)	11.63 (9.97)
Distance between home to the workplace (km)	8.25 (10.96)

accounts for 22.2% of the total variance. In terms of other characteristics, including the distance from the city center to workplaces, greenery, land use entropy, and floor area ratio all contribute no less than 8%.

Similarly, the built environment explains a large proportion of recreational walking variation, accounting for 81.6% of the total variance. The distance from home to the workplace accounts for the largest proportion. The distance from the city center to workplaces, land use entropy, number of physical activity facilities, street view greenery, and floor area ratio, contribute approximately 8–12%.

To summarize, the relative contribution of the different independent variables tends to be steady in explaining three domains of walking. Distance from home to workplace accounts for the largest variance in all three walking categories, whereas having access to a metro station within 1000 m contributes to the least variance among the different built environment attributes. Notably, the number of physical activity facilities plays a more important role in utilitarian and recreational walking, compared with commuting walking. Among the individual-level variables, age and duration of employment in the current job are central indicators in predicting walking behavior.

4.3. *Non-linear associations of the built environment with different walking types*

4.3.1. *Commuting walking*

The partial dependence plot illustrates the relationships between the built environment and the different types of walking behaviors. Notably, the tick on the x-axis represents the distribution of the predictor variables in the whole range. Fig. 2 presents the association between the built environment and commuting walking after controlling for individual-level covariates. When the distance from home to the workplace is less than 10 km, it is negatively associated with commuting walking. However, it has a positive effect between the range of 10–20 km, and the effects become saturated when the distance exceeds 20 km. The floor area ratio is positively associated with commuting walking when it is smaller than 0.6, but once the ratio exceeds the cut-off point, it shows a negative association with commuting walking. For land use entropy, walking time increases rapidly when the entropy index exceeds 2.2; road intersection has a negative association with commuting walking when it is less than 50. Street view greenery is negatively associated with commuting walking. Distance from the city center to workplaces is also negatively correlated with commuting walking. In addition, the number of facilities physical activity facilities is positively associated with commuting walking.

4.3.2. *Utilitarian walking*

Fig. 3 shows the associations between the attributes of the built environment and utilitarian walking. Specifically, distance from home to the workplace and floor area ratio are negatively associated with utilitarian walking. In terms of land use entropy, its influence is steady, but it exerts a negative influence on utilitarian walking when it is larger than 1.7. Although this result fluctuates, higher level of street view greenery increases the likelihood of partaking in utilitarian walking. A greater distance between the city center and workplaces is also negatively associated with utilitarian walking. Mixed land-use patterns are negatively correlated with utilitarian walking. Furthermore, the influence of physical activity facilities is steady for most observations; however, once the numbers exceed 1000, they exert profound effects on the level of utilitarian walking.

4.3.3. *Recreational walking*

Fig. 4 illustrates the association between the built environment of workplace neighborhoods and recreational walking. Both longer distance from home to the workplace and higher floor area ratio will curb recreational walking. Notably, higher levels of land use entropy and street view greenery are positively associated with recreational walking. Road intersection shows a complex relationship with recreational walking; it is negatively associated with recreational walking when the intersections are less than 50, but once the ratio exceeds 100, it greatly encourages recreational walking. Greater distance between the city center and workplaces is found to be negatively associated with recreational walking. Consistent with other walking behaviors, physical activity facilities also encourage walking.

Table 3
Relative importance of the covariates in predicting different domains of walking

Variable		Commuting walking			Utilitarian walking			Recreational walking		
		Relative importance in explaining commuting walking (%)	Rank	Summarized contribution	Relative importance in explaining utilitarian walking (%)	Rank	Summarized contribution	Relative importance in explaining recreational walking (%)	Rank	Summarized contribution
Built environment attributes	Distance between home to the workplace	28.2	1	75.6	16.1	1	86.2	20.7	1	81.6
	Floor area ratio	10.6	2		9.5	4		8.8	6	
	Land use entropy	8.6	3		8.0	8		11.6	3	
	Number of road intersection	8.2	4		9.4	5		7.5	7	
	Street view greenery	8.1	5		9.6	3		8.9	5	
	Distance from the city center to workplaces	7.8	6		8.6	6		11.7	2	
	Number of physical activity facilities	5.3	7		9.6	2		10.6	4	
	Number of parks	2.9	11		3.0	10		1.4	10	
	Metro station within 1000 m	0.6	16		1.9	14		0.3	15	
Individual-level attributes	Age	5.1	8	24.4	8.2	7	13.8	7.4	8	18.4
	Employment duration in the current job	5.1	9		6.8	9		7.1	9	
	Self-rated overall health	3.1	10		0.9	16		0.7	12	
	Shanghai *hukou*	2.1	12		0.7	12		0.3	18	
	College and above	1.2	13		0.6	18		0.4	17	
	Female	1.0	14		2.4	11		1.0	11	
	Mid household income	0.7	15		1.2	13		0.6	14	
	High school	0.9	17		0.8	17		0.6	13	
	High household income	0.4	18		0.5	19		0.4	16	
	Marital status	0.2	19		1.1	15		0.1	19	

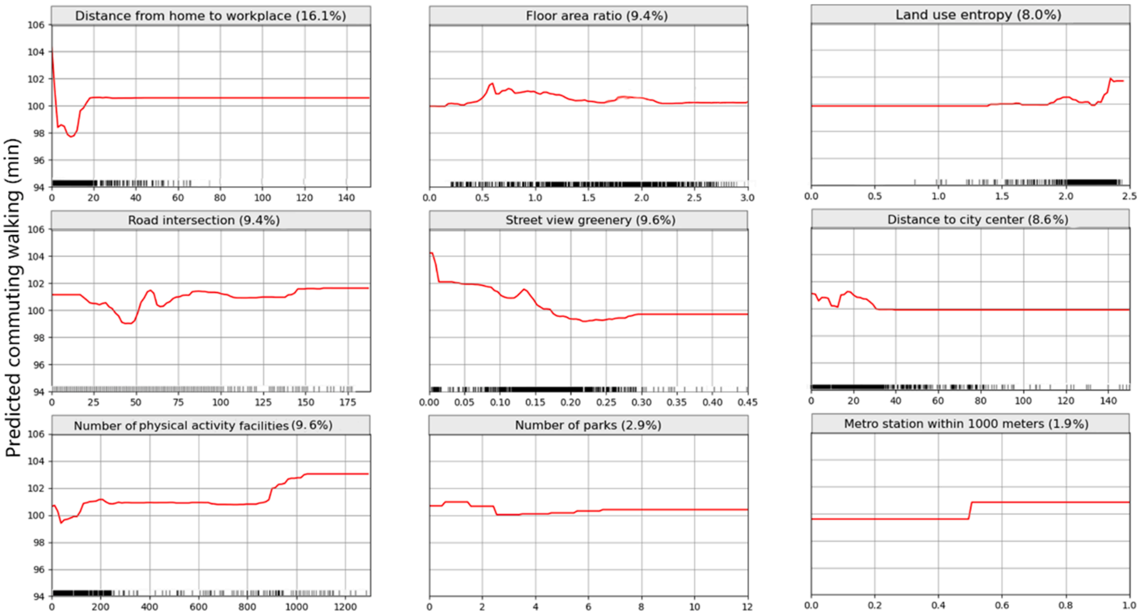

Fig. 2. Non-linear relationships between the built environment attributes and commuting walking.

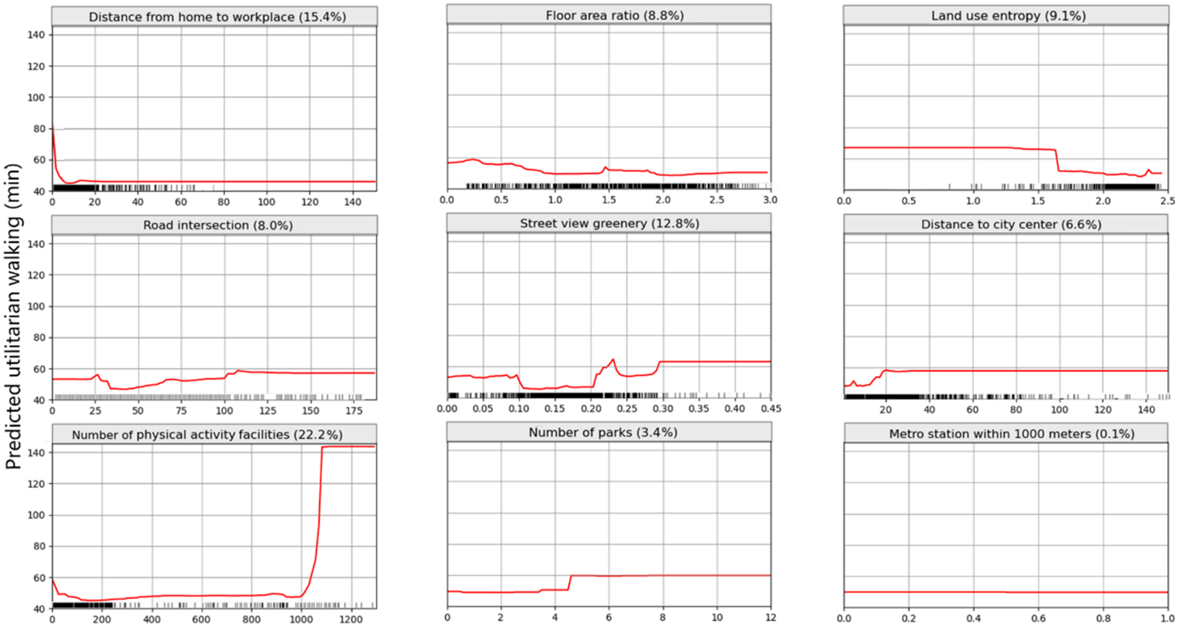

Fig. 3. Non-linear relationships between the built environment attributes and utilitarian walking.

4.4. Comparison with conventional linear regression

Table S2–S4 in the supplementary materials show the coefficient and relative importance of the independent variables. These tables illustrate that the relative importance of independent variables tend to differ between the GBDT and the linear regression, and the results of the GBDT suggest a greater contribution of the built environment attributes and better goodness of fit. Given that GBDT is more effective in revealing non-linear relationships, the initial assumption of an association between independent variables and walking behavior in the linear regression is flawed.

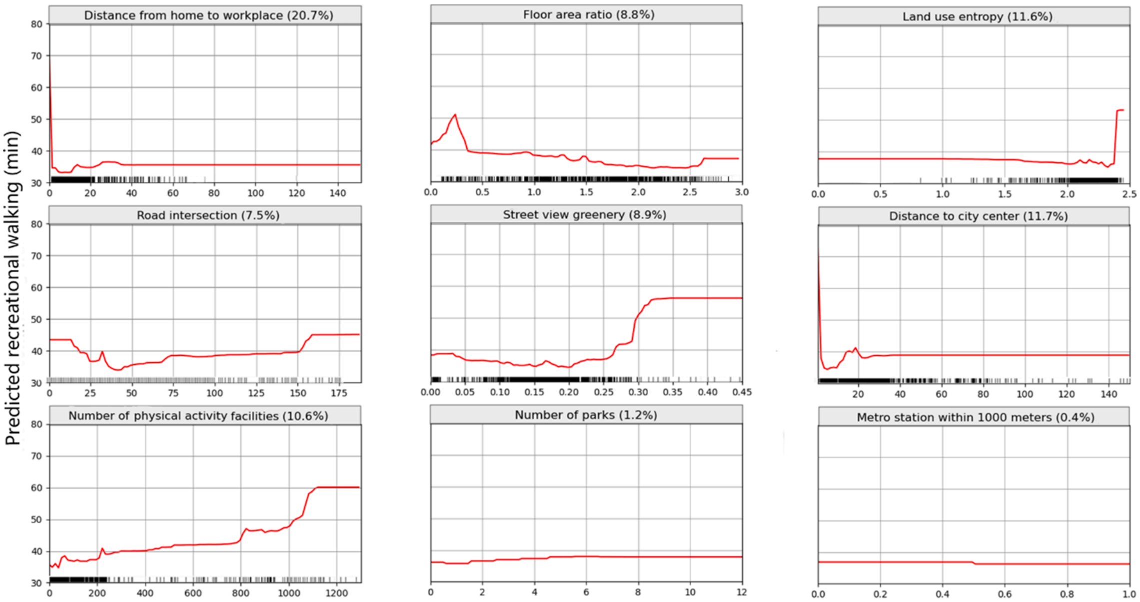

Fig. 4. Non-linear relationships between the built environment attributes and recreational walking.

4.5. *Robustness test*

For more than 10% of the respondents, their residential neighborhoods are adjacent to their workplace neighborhood. Therefore, reported individuals' walking behaviors may be similar in two settings. As a sensitivity analysis, we excluded those respondents whose residential neighborhood was less than 500 m from their workplace (final sample = 869). The results appear to be robust and only minor changes in the associations are observable, except for the distance between the city center and workplaces (Fig. S1–S3).

5. Discussion

Promoting walking and other types of physical activity is critical for achieving the goals of sustainable transportation and healthy cities. Given the recently suggested complex relationship between the built environment and walking behaviors (Zhao & Wan, 2020), this study is one of the first to explore the non-linear associations between the built environment around workplaces and three domains of walking behaviors among working adults in Shanghai, China.

There are three categories of findings in this study. First, based on the results of the GBDT models, the built environment around workplaces has a much larger effect on walking behaviors than individual-level attributes. Thus, this study confirmed that the built environment around workplaces is crucial in shaping walking behaviors in high-density cities in developing countries. Specifically, several built environment attributes showed associations with all domains of walking behaviors, such as physical activity facilities, floor area ratio, and road intersections. Nearby physical activity facilities provided attractive places for employees, stimulated transportation walking to these places, as well as improved walking levels when using these facilities. A higher floor area ratio was negatively associated with walking behaviors, possibly because of the constraints of a crowded environment. In addition, we found a relatively weak or even negative influence of road intersections on different walking types. It seems that congestion and safety issues in areas with high inter-street connectivity may hinder transportation walking in the business areas of Shanghai. Hence, it is possible that employees prefer to choose public transport for a more pleasant experience. These results are in line with a study in Beijing but contradict findings in Western settings (Zhao & Wan, 2020).

Second, variations exist in the effects of the built environment attributes on different domains of walking. Regarding the complex relationship between distance from home to workplaces and commuting walking, it seemed that individuals switch from walking to motorized transportation modes when commuting distances increase. In contrast, when they used mixed modes (e.g., both public transit and walking) for long-distance trips, the walking time increased again. The results regarding utilitarian and recreational walking implied that stressful and long-distance commuting may also constrain people's time flexibility and willingness to walk for errands and leisure activities around workplaces. Higher land use entropy may increase the likelihood of commuting and recreational walking but not increase utilitarian walking. Prior studies have suggested that workplace neighborhoods with a good mixture of land use may provide more destinations within accessible walking distance (Gehrke & Welch, 2017). However, observations from utilitarian walking did not fully support this conclusion. Evidently, a high level of diversity in land use around workplaces reduces utilitarian walking time by providing an opportunity to finish several utilitarian activities in a single walking trip.

Third, some findings contradict prior findings dealing with the residential environment. In this study, street view greenery's positive associations with utilitarian and recreational walking are consistent with previous results (Yang et al., 2021b), whereas its negative association with commuting walking is unexpected. One explanation could be that higher levels of greenery around the workplace also promote alternative non-motorized modes (e.g., e-scooter and bicycles). Given that working adults in Shanghai have an incentive to minimize time and energy for commuting, the positive effects on walking are hindered. Another explanation could be that the promotion effects of street greenery depend on the level and quality of the streets. For instance, a study revealed that street greenery has a two-way impact on active travel distance, and the association is positive only when active travel takes place on low-rank streets (Wu et al., 2020). In this study, the distance between the city center to workplaces had distinctive relationships with different domains of walking. It was positively associated with utilitarian walking and negatively correlated with commuting and recreational walking. Regarding commuting, suburban workplaces generally have limited public transport stops; thus, commuters tend to prefer motorized modes for long-distance commuting trips (Sun, Ermagun, & Dan, 2017). For utilitarian walking, since different facilities were sparse in suburban areas, employees in workplaces far from central business areas often undertook longer walking trips to arrive at/from different facilities (e.g., shops, pharmacies, and gyms). Workplaces in suburban areas comprised less attractive places, which may discourage people from engaging in more recreational walking.

The non-linear association between the built environment around workplaces and walking could provide input for creating pedestrian-friendly workplaces in high-density cities. First, the relationships between the built environment attributes and walking behaviors are complex and domain specific. The conclusions derived from different residential neighborhoods cannot be directly applied to workplaces, as distinctive mechanisms may trigger walking behaviors in different daily activity spaces. When conducting environmental intervention projects, the behaviors patterns of the working population and residents in the neighborhoods should be considered jointly. Second, the built environment attributes that affect different domains of walking should be further emphasized in intervention projects. For instance, creating more physical activity facilities and restricting over-crowded developments are feasible urban design options. Third, constrained by investment budgets and difficulties in modifying the built environment, non-linear relationships and thresholds obtained through our non-linear models could support decision making. For example, street greenery beyond 0.3 and land use entropy smaller than 1.7 have limited effects on walking behaviors. Ignoring such threshold values may lead to inappropriate active transport policies.

This study had several limitations. First, the measurement of walking behaviors relied on self-reported data, thus, values may consequently be overestimated due to recall bias and social-desirability bias (Motl, McAuley, & DiStefano, 2005). Future studies should be based on objectively measured walking data using accelerometers and global positioning system (GPS)-based tracking data. Second, the cross-sectional nature of the data precluded inferred causality. Third, due to a lack of data on people's attitudes toward walking, the associations may be overestimated. Fourth, the built environment was measured within 1,000-meter circular buffer centered on workplaces. Assessing built environments with different buffer sizes could alter the reported associations (Wang et al., 2021). In addition, we failed to consider the heterogeneity of family structures (e.g., household members and children), which has been highlighted extensively in previous studies.

6. Conclusion

Our study is among the first to investigate non-linear associations between the built environment around workplaces and different domains of walking behaviors of the working population. Our results suggest overall strong associations of the built environment attributes with walking behaviors, but built environment feature have different associations with different domains of walking. Specifically, the number of physical activity facilities was positively associated with all three walking behaviors, and high floor area ratio was negatively associated with three domains of walking. Furthermore, several built environment characteristics, such as land use entropy, street view greenery, distance between the city center and workplaces, and distance from home to the workplace, showed distinctive associations with different walking behaviors. Policymakers and urban planners should consider non-linear relationships between the built environment and walking behaviors, and utilize threshold effects to develop effective environmental interventions when designing environments around workplaces.

Credit authorship contribution statement

Haoran Yang: Conceptualization, Methodology, Supervision, Writing – review & editing. **Qinran Zhang:** Methodology, Formal analysis. **Marco Helbich:** Writing – review & editing. **Yi Lu:** Writing – review & editing. **Dongsheng He:** Conceptualization, Methodology, Formal analysis, Original draft. **Dick Ettema:** Writing – review & editing. **Long Chen:** Data collection.

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.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tra.2021.11.017.

References

Adams, E.J., Bull, F.C., Foster, C.E., 2016. Are perceptions of the environment in the workplace ‘neighbourhood’ associated with commuter walking? J. Transp. Health 3 (4), 479–484.

Adlakha, D., Hipp, A.J., Marx, C., Yang, L., Tabak, R., Dodson, E.A., Brownson, R.C., 2015. Home and workplace built environment supports for physical activity. Am. J. Prev. Med. 48 (1), 104–107.

Breiman, L., 2001. Random forests. Machine Learning 45 (1), 5–32.

Carlson, J.A., Frank, L.D., Ulmer, J., Conway, T.L., Saelens, B.E., Cain, K.L., Sallis, J.F., 2018. Work and home neighborhood design and physical activity. Am. J. Health Promot. 32 (8), 1723–1729.

Cerin, E., Nathan, A., Van Cauwenberg, J., Barnett, D.W., Barnett, A., 2017. The neighbourhood physical environment and active travel in older adults: a systematic review and meta-analysis. Int. J. Behav. Nutrit. Phys. Activity 14 (1), 1–23.

Chaix, B., Duncan, D., Vallée, J., Vernez-Moudon, A., Benmarhnia, T., Kestens, Y., 2017. The “residential” effect fallacy in neighborhood and health studies. Epidemiology 28 (6), 789–797.

Chan, E.T., Schwanen, T., Banister, D., 2019. The role of perceived environment, neighbourhood characteristics, and attitudes in walking behaviour: evidence from a rapidly developing city in China. Transportation 1–24.

Cheng, L., De Vos, J., Zhao, P., Yang, M., Witlox, F., 2020. Examining non-linear built environment effects on elderly’s walking: a random forest approach. Transport. Res. art D: Transp. Environ. 88, 102552.

Christiansen, L.B., Cerin, E., Badland, H., Kerr, J., Davey, R., Troelsen, J., van Dyck, D., Mitáš, J., Schofield, G., Sugiyama, T., Salvo, D., Sarmiento, O.L., Reis, R., Adams, M., Frank, L., Sallis, J.F., 2016. International comparisons of the associations between objective measures of the built environment and transport-related walking and cycling: IPEN adult study. J. Transp. Health 3 (4), 467–478.

Cordts, M., Omran, M., Ramos, S., Rehfeld, T., Enzweiler, M., Benenson, R., Schiele, B., 2016. The cityscapes dataset for semantic urban scene understanding. In: In Proceedings of the IEEE conference on computer vision and pattern recognition, pp. 3213–3223.

Ding, C., Cao, X.J., Næss, P., 2018. Applying gradient boosting decision trees to examine non-linear effects of the built environment on driving distance in Oslo. Transport. Res. A: Pol. Pract. 110, 107–117.

Ekelund, U., Steene-Johannessen, J., Brown, W.J., Fagerland, M.W., Owen, N., Powell, K.E., Bauman, A., Lee, I.-M., 2016. Does physical activity attenuate, or even eliminate, the detrimental association of sitting time with mortality? A harmonised meta-analysis of data from more than 1 million men and women. The Lancet 388 (10051), 1302–1310.

Forsyth, A., Oakes, J.M., Schmitz, K.H., Hearst, M., 2007. Does residential density increase walking and other physical activity? Urban Studies 44 (4), 679–697.

Friedman, J.H., 2001. Greedy function approximation: a gradient boosting machine. Ann. Stat. 1189–1232.

Gao, J., Kamphuis, C.B., Ettema, D., Helbich, M., 2019. Longitudinal changes in transport-related and recreational walking: the role of life events. Transport. Res. D: Transp. Environ. 77, 243–251.

Gehrke, S.R., Welch, T.F., 2017. The built environment determinants of activity participation and walking near the workplace. Transportation 44 (5), 941–956.

Hagenauer, J., Helbich, M., 2017. A comparative study of machine learning classifiers for modeling travel mode choice. Expert Syst. Appl. 78, 273–282.

He, D., Lu, Y., Xie, B., Helbich, M., 2021. Large-scale greenway intervention promotes walking behaviors: A natural experiment in China. Transport. Res. D: Transp. Environ. 101, 103095.

Hipp, J.A., Dodson, E.A., Lee, J.A., Marx, C.M., Yang, L., Tabak, R.G., Hoehner, C., Marquet, O., Brownson, R.C., 2017. Mixed methods analysis of eighteen worksite policies, programs, and environments for physical activity. Int. J. Behav. Nutrit. Phys. Activity 14 (1). https://doi.org/10.1186/s12966-017-0533-8.

Jack, E., McCormack, G.R., 2014. The associations between objectively-determined and self-reported urban form characteristics and neighborhood-based walking in adults. Int. J. Behav. Nutrit. Phys. Activity 11 (1), 71. https://doi.org/10.1186/1479-5868-11-71.

Kang, B., Moudon, A.V., Hurvitz, P.M., Saelens, B.E., 2017. Differences in behavior, time, location, and built environment between objectively measured utilitarian and recreational walking. Transport. Res. D: Transp. Environ. 57, 185–194.

Kamruzzaman, M.d., Washington, S., Baker, D., Brown, W., Giles-Corti, B., Turrell, G., 2016. Built environment impacts on walking for transport in Brisbane, Australia. Transportation 43 (1), 53–77.

Kerr, J., Emond, J.A., Badland, H., Reis, R., Sarmiento, O., Carlson, J., Sallis, J.F., Cerin, E., Cain, K., Conway, T., Schofield, G., Macfarlane, D.J., Christiansen, L.B., Van Dyck, D., Davey, R., Aguinaga-Ontoso, I., Salvo, D., Sugiyama, T., Owen, N., Mitáš, J., Natarajan, L., 2016. Perceived neighborhood environmental attributes associated with walking and cycling for transport among adult residents of 17 cities in 12 countries: the IPEN study. Environ. Health Perspect. 124 (3), 290–298.

Koohsari, M.J., Sugiyama, T., Lamb, K.E., Villanueva, K., Owen, N., 2014. Street connectivity and walking for transport: role of neighborhood destinations. Prev. Med. 66, 118–122.

Kroesen, M., De Vos, J., 2020. Does active travel make people healthier, or are healthy people more inclined to travel actively? J. Transp. Health 16, 100844. https://doi.org/10.1016/j.jth.2020.100844.

Lee, I.M., Shiroma, E.J., Lobelo, F., Puska, P., Blair, S.N., Katzmarzyk, P.T., 2012. Impact of physical inactivity on the world’s major non-communicable diseases. Lancet 380 (9838), 219–229.

Lin, C.-Y., Koohsari, M.J., Liao, Y., Ishii, K., Shibata, A.i., Nakaya, T., McCormack, G.R., Hadgraft, N., Owen, N., Oka, K., 2020. Workplace neighbourhood built environment and workers’ physically-active and sedentary behaviour: a systematic review of observational studies. Int. J. Behav. Nutrit. Phys. Activity 17 (1). https://doi.org/10.1186/s12966-020-01055-x.

Liu, Y., Wang, X., Zhou, S., Wu, W., 2020. The association between spatial access to physical activity facilities within home and workplace neighborhoods and time spent on physical activities: evidence from Guangzhou, China. Int. J. Health Geograp. 19 (1), 1–15.

Lu, Y., Sarkar, C., Xiao, Y., 2018. The effect of street-level greenery on walking behavior: evidence from Hong Kong. Soc. Sci. Med. 208, 41–49.

Lu, Y., Sun, G., Gou, Z., Liu, Y., Zhang, X., 2019. A dose–response effect between built environment characteristics and transport walking for youths. J. Transp. Health 14, 100616. https://doi.org/10.1016/j.jth.2019.100616.

Marquet, O., Floyd, M.F., James, P., Glanz, K., Jennings, V., Jankowska, M.M., Kerr, J., Hipp, J.A., 2020. Associations between worksite walkability, greenness, and physical activity around work. Environ. Behav. 52 (2), 139–163.

Mirzaei, E., Kheyroddin, R., Behzadfar, M., Mignot, D., 2018. Utilitarian and hedonic walking: examining the impact of the built environment on walking behavior. Eur. Transp. Res. Rev. 10 (2), 20.

Mokhtarian, P.L., Salomon, I., 2001. How derived is the demand for travel? Some conceptual and measurement considerations. Transport. Res. A: Pol. Pract. 35 (8), 695–719.

Motl, R., Mcauley, E., Distefano, C., 2005. Is social desirability associated with self-reported physical activity? Prev. Med. 40 (6), 735–739.

Ng, S.W., Howard, A.-G., Wang, H.J., Su, C., Zhang, B., 2014. The physical activity transition among adults in China: 1991–2011. Obes. Rev. 15, 27–36.

Ridgeway, G., 2007. Generalized boosted models: A guide to the gbm package. Update 1 (1), 2007.

Sallis, J.F., Owen, N., Fisher, E., 2015. Ecological models of health behavior. Health Behav.: Theory Res. Pract. 5 (43–64).

Schonlau, M., 2005. Boosted regression (boosting): an introductory tutorial and a stata plugin. Stata J. 5 (3), 330–354.

Schwartz, M.A., Aytur, S.A., Evenson, K.R., Rodríguez, D.A., 2009. Are perceptions about worksite neighborhoods and policies associated with walking? Am. J. Health Promot. 24 (2), 146–151.

Shanghai Municipal Statistics Bureau, 2019. Shanghai Statistical Yearbook 2018. Derived from: http://tjj.sh.gov.cn/tjnj/20190117/0014-1001529.html.

Sun, B., Ermagun, A., Dan, B., 2017. Built environmental impacts on commuting mode choice and distance: evidence from Shanghai. Transport. Res. D: Transp. Environ. 52, 441–453.

Sun, G., Webster, C., Chiaradia, A., 2017. Objective assessment of station approach routes: Development and reliability of an audit for walking environments around metro stations in China. J. Transport Health 4, 191–207.

Sun, G., Zhao, J., Webster, C., Lin, H., 2020. New Metro system and active travel: a natural experiment. Environ. Int. 138, 105605.

Ussery, E.N., Carlson, S.A., Whitfield, G.P., Watson, K.B., Berrigan, D., Fulton, J.E., 2018. Transportation and leisure walking among US adults: trends in reported prevalence and volume, National Health Interview Survey 2005–2015. Am. J. Prev. Med. 55 (4), 533–540.

Vale, D.S., Pereira, M., 2016. Influence on pedestrian commuting behavior of the built environment surrounding destinations: A structural equations modeling approach. Int. J. Sustain. Transport. 10 (8), 730–741.

Van Dyck, D., Cerin, E., Conway, T.L., De Bourdeaudhuij, I., Owen, N., Kerr, J., Sallis, J.F., 2013. Perceived neighborhood environmental attributes associated with adults' leisure-time physical activity: findings from Belgium, Australia and the USA. Health & Place 19, 59–68.

Van Uffelen, J.G., Wong, J., Chau, J.Y., Van Der Ploeg, H.P., Riphagen, I., Gilson, N.D., Gardiner, P.A., 2010. Occupational sitting and health risks: a systematic review. Am. J. Prev. Med. 39 (4), 379–388.

Van Wee, B., Handy, S., 2016. Key research themes on urban space, scale, and sustainable urban mobility. Int. J. Sustain. Transport. 10 (1), 18–24.

Vogel, T., Brechat, P.H., Leprêtre, P.M., Kaltenbach, G., Berthel, M., Lonsdorfer, J., 2009. Health benefits of physical activity in older patients: a review. Int. J. Clin. Pract. 63 (2), 303–320.

Wang, Z., Ettema, D., Helbich, M., 2021. Objective environmental exposures correlate differently with recreational and transportation walking: a cross-sectional national study in the Netherlands. Environ. Res. 110591.

Wu, J., Wang, B., Ta, N., Zhou, K., Chai, Y., 2020. Does street greenery always promote active travel? Evidence from Beijing. Urban For. Urban Greening 56, 126886. https://doi.org/10.1016/j.ufug.2020.126886.

Wu, X., Tao, T., Cao, J., Fan, Y., Ramaswami, A., 2019. Examining threshold effects of built environment elements on travel-related carbon-dioxide emissions. Transport. Res. D: Transp. Environ. 75, 1–12.

Yang, Y., He, D., Gou, Z., Wang, R., Liu, Y., Lu, Y., 2019. Association between street greenery and walking behavior in older adults in Hong Kong. Sustain. Cities Soc. 51, 101747.

Yang, H., He, D., Lu, Y., Ren, C., Huang, X., 2021a. Disentangling residential self-selection from the influence of built environment characteristics on adiposity outcomes among undergraduate students in China. Cities 113, 103165. https://doi.org/10.1016/j.cities.2021.103165.

Yang, L., Ao, Y., Ke, J., Lu, Y., Liang, Y., 2021b. To walk or not to walk? Examining non-linear effects of streetscape greenery on walking propensity of older adults. J. Transp. Geogr. 94, 103099. https://doi.org/10.1016/j.jtrangeo.2021.103099.

Ye, Y., Richards, D., Lu, Y., Song, X., Zhuang, Y., Zeng, W., Zhong, T., 2019. Measuring daily accessed street greenery: A human-scale approach for informing better urban planning practices. Landscape Urban Plann. 191, 103434. https://doi.org/10.1016/j.landurbplan.2018.08.028.

Yue, Y., Zhuang, Y., Yeh, A.G.O., Xie, J., Ma, C., Li, Q., 2017. Measurements of POI-based mixed use and their relationships with neighbourhood vibrancy. Int. J. Geogr. Informat. Sci. 31 (4), 658–675.

Zhao, P., Wan, J., 2020. Examining the effects of neighbourhood design on walking in growing megacity. Transport. Res. D: Transp. Environ. 86, 102417.