Examining the spatially heterogeneous effects of the built environment on walking among older adults

Abstract

Understanding the relationship between the built environment and walking among older adults could offer important insights for land use and transport policies which seek to promote active ageing. However, most previous studies have explored global relationships, i.e. the effects are averaged or assumed to be constant over the region of interest. In this study, we focus on the local spatial variations in the relationship between the built environment and the daily time spent walking by older adults. We apply a geographically weighted regression (GWR) model, using data collected from 702 older adults in Nanjing, China. Our results show that spatial heterogeneity exists for built environment effects within the entire study area. It has an impact on all the relationships, with nuances in the significance level, parameter magnitude or sign reversals, depending on the location. Therefore, policy interventions would only be effective in certain areas for certain built environment attributes. By exploring the local contexts of relationships, we further suggest that the spatial heterogeneity stems from contextual effects, i.e. the specificities of places with a discriminative composition of individual and/or environmental characteristics. Our findings can help to enrich the understanding of associations between land use and travel behaviour, as well as offer local planning guidance for creating age-friendly neighbourhoods.

Keywords

Built environment; Land use; Walking; Older adults; Active ageing; Spatial heterogeneity

1. Introduction

The increasing life expectancy and declining mortality rate over the past few decades have substantially changed the traditional demographic pyramid. The world population is now distributed more towards older age groups. As of 2019, the number of older people (aged 65 or over) reached 703 million, which accounts for 9% of the global population (UN, 2019). The United Nations (2019) has projected that the proportion will further rise to 12% in 2030 and 16% in 2050. Demographic ageing has highlighted the need for interventions which could improve the quality of life for older adults. Walking, an important form of active travel, has been attracting policy attention as a useful instrument with which to support active ageing (Cheng et al., 2019b; Curl and Mason, 2019; Forsyth et al., 2007; Moniruzzaman and Páez, 2016). Walking benefits the functional wellness of older adults through physical activity performed while moving. Since the World Health Organisation (WHO, 2010) recommends no less than 150 minutes of moderate physical activity every week for older people, walking could make a significant contribution to keeping healthy. In addition, as a form of mobility, walking provides opportunities for social cohesion and participation by enabling access to destinations and services. This in turn fosters a sense of independence, self-efficacy, and wellbeing among older adults (Nordbakke and Schwanen, 2014).

A number of existing studies have examined built environment correlates of walking among older adults (e.g. Cerin et al., 2014, 2017; Figueroa et al., 2014; Leen and Dean, 2018). Some research found significant relationships between the built environment and walking, and emphasised that built environment interventions can increase the likelihood of walking (Böcker et al., 2017; Cheng et al., 2019c; Leen and Dean, 2018). However, in other studies, no statistically significant or even contrasting relationships were detected (Cerin et al., 2014; Christiansen et al., 2016; Foster and Giles-Corti, 2008; Hirsh et al., 2016). These mixed findings could be the result of two factors. One is related to the different measurements of data and/or modelling procedures used in these studies. For instance, explanatory variables relating to the built environment could rely on objective calculations or individuals' perceptions (Cerin et al., 2014). Moreover, some studies account for moderators or confounders, but others do not, or at least not the same ones. These covariates, however, may affect model estimations. The other important explanation is the structural instability of regression parameters across locations, where associations are strong in some areas but moderate in others (Feuillet et al., 2016; Mitra and Buliung, 2014). In other words, the spatial heterogeneity of relationships is likely to be a source of these inconsistent findings. This indicates that exposure to the same environmental attributes may result in different outcomes over space (Páez, 2006).

Spatial heterogeneity has frequently been analysed on various scales for different outcomes, including rail demand (Blainey, 2010), pedestrian crash frequency (Chen and Zhou, 2016), activity space (Chen et al., 2017), transport accessibility (Cheng et al., 2019a; Cuthill et al., 2019), and ride-sourcing demand (Yu and Peng, 2019). Examining land use-travel behaviour associations purely on a global scale could hide some potentially vital information about the spatial patterns of relationships (Kim et al., 2019; Páez, 2006; Yang et al., 2017). However, the majority of studies relating to older adults' travel behaviour have looked at the global relationships over the study area (see Barnett et al. (2017) and Cerin et al. (2017) for an overview). More importantly, there has been a lack of investigation into the mechanism behind the spatial heterogeneity of relationships. Against this backdrop, this study aims to investigate how, and why, the effects of the built environment on walking among older adults vary across space.

The contribution of the present study is twofold. Empirically, we identify spatially varying built environment correlates of older adults' walking. The revealed spatial heterogeneity of relationships can help to offer nuanced policy interventions designed to promote walking. Theoretically, it advances the understanding of associations between land use and travel behaviour by exploring the local contexts of spatial clusters in relation to walking. Spatial heterogeneity could result from the contextual effect of places with a certain composition of individual and/or environmental characteristics. The rest of the paper is structured into five sections. Section 2 reviews the literature about the effects of the built environment on older adults' walking. This is followed by Section 3 which presents the data collected and explains the geographically weighted regression model. Section 4 discusses the research findings, while Section 5 concludes the study by summarising the key results.

2. Literature review

The relationship between the built environment and walking among older adults has been well documented in the literature (Gómez et al., 2010; Kemperman and Timmermans, 2009; Li et al., 2005; van Cauwenberg et al., 2013). A meta-analysis conducted by Cerin et al. (2017) showed that walking is significantly associated with a range of environmental attributes, such as residential density, land use mix, urban design, street connectivity, access to destinations, and public transport accessibility. Neighbourhood-level population density is the most frequently analysed land use attribute in these studies and is found to increase the likelihood of walking (Böcker et al., 2017; Liao et al., 2018). A higher level of mixed land use has also been proven to be positively associated with the propensity to walk among older adults (Leung et al., 2018; Moniruzzaman et al., 2013). Hou (2019) analysed the influence of access to cultural facilities (i.e. places of worship) on walking trips among senior citizens and derived a positive association. There is evidence that the frequency and duration of walking among older adults increases if their homes are near to recreational amenities, e.g. parks, squares or greenspaces (Cheng et al., 2019b; Leung et al., 2018). Older adults with better access to public transport also tend to walk more, which is demonstrated by empirical studies conducted in the US (Suminski et al., 2005) and Canada (Barnes et al., 2016), for example. In addition, the pleasantness and aesthetics of the environment (e.g. good quality open spaces, presence of parks or waterways, low-level air pollution exposure) are found to be facilitators of walking (Kerr et al., 2016).

However, other studies have presented inconsistent findings. Cerin et al. (2014) noted that there was no association between residential density and walking among older people in Hong Kong. In this regard, Christiansen et al. (2016) conducted a multi-country comparison and identified that the odds of walking became saturated or even decreased after residential density reached a certain threshold (approximately 12,000 dwellings/km^2). In Luxembourg, Perchoux et al. (2019) described a negative relationship between older adults' walking and street connectivity in neighbourhoods with a high degree of street connectivity (more than eight intersections within buffered areas). Reverse relationships have also been found between the degree of urbanisation and the propensity to walk in studies by Kemperman and Timmermans (2009) and Hou (2019). The former revealed a positive association, while the latter showed a negative relationship. Several researchers have reported differing results regarding access to destinations and services. For instance, Chaix et al. (2016) identified positive correlations between walking and the density of services at both trip origin and destination points. In contrast, Hirsh et al. (2016) reported no correlation between walking among older adults and the density of destinations. In addition, although Hou (2019) found that the availability of religious destinations was a facilitator for older adults' walking, no such association was reported by Barnett et al. (2017). In terms of access to greenspaces/parks, an International Physical Activity and the Environment Network (IPEN) adult study observed no overall associations with the frequency of walking (Christiansen et al., 2016). Older adults in Montreal (Canada) and Singapore were found to be even less likely to walk if their residence was near to parks and playgrounds (Hou, 2019; Moniruzzaman and Páez, 2016). There is also contrary evidence regarding access to public transport: Perchoux et al. (2019) observed detrimental impacts, while Suminski et al. (2005) and Barnes et al. (2016) reported favourable influences. The role of environmental quality is also worth noting. Foster and Giles-Corti (2008) found that some older people regularly engaged in walking regardless of the aesthetics and safety issues in the neighbourhood. This finding conflicts with those of previous studies which have identified positive relationships (Barnett et al., 2017; Kerr et al., 2016).

Spatial heterogeneity is likely to be an important source of these inconsistent results among empirical studies (Feuillet et al., 2018; Páez, 2006). It refers to differences in relationships between the outcome and explanatory variables across spatial units within a study area (Fotheringham et al., 2002). Tobler's first law of geography posits that observations at nearby locations are more closely related than those which are farther away (Tobler, 1970). Spatial data are always generated distinctively across geographical locations (Fotheringham and Brunsdon, 1999). This spatial non-stationary process that operates within the data means that studies on land use and travel behaviour need to take local associations into account rather than focusing only on global associations (Bhat and Zhao, 2002). There is a growing recognition among transport planners of the need to improve understanding of spatially varying correlates of travel behaviour (Chen et al., 2017; Liu et al., 2016; Yu and Peng, 2019). This is credited to the useful information obtained which could guide localised planning practice. For instance, Mitra and Buliung (2014) noted that the effects of the built environment on travel mode choice are not spatially uniform across neighbourhoods. Local estimates would be very helpful in identifying target areas for effective infrastructure provision. Yu and Peng (2019) examined spatial differences in the relationship between the built environment and ride-sourcing demand and prescribed nuanced transport planning and urban governance measures. In particular, Ding et al. (2018) made an important point that ignoring the spatial heterogeneity of relationships leads to erroneous estimates of built environment effects and inappropriate policy implications.

The link between the built environment and walking is also context specific. Feuillet et al. (2016, 2018) confirmed the existence of their spatially varying relationships: spatial patterns of associations can be positive or negative, depending on the location of observations. However, prior research into older adults' walking behaviour has often overlooked the consequences of spatial heterogeneity, i.e. results are averaged or assumed to be constant for the entire region of interest. In line with the principle of spatial heterogeneity, it is likely that the strengths of built environment effects on walking among older adults will change at a local level. Capturing these variations could offer planners accurate estimations and support place-based interventions (Kim et al., 2019) with which to effectively encourage active ageing. Therefore, this research attempts to address the aforementioned gaps by examining the spatially heterogeneous effects of the built environment on walking among older adults.

3. Methods

3.1. Study area and data

We investigated the daily time that older adults spent walking based on the 2013 Nanjing Household Travel Survey. Nanjing, the capital of Jiangsu Province in China, offers an interesting case study as walking is the dominant means of travel among the older population. We focused on the main city area which covers five districts: Gulou, Xuanwu, Jianye, Qinhuai, and Yuhuatai (Figure 1). It is further partitioned into 49 sub-districts, which are the basic territorial units for urban governance and administration. The main city has a total area of 393 km^2 and is home to over 3.75 million inhabitants with the proportion of older adults (60+ years old) being 22% (Nanjing Municipal Bureau Statistics, 2019). More than 0.80 million older adults live in this study area, with the population density of older adults being 2,335 persons/km^2.

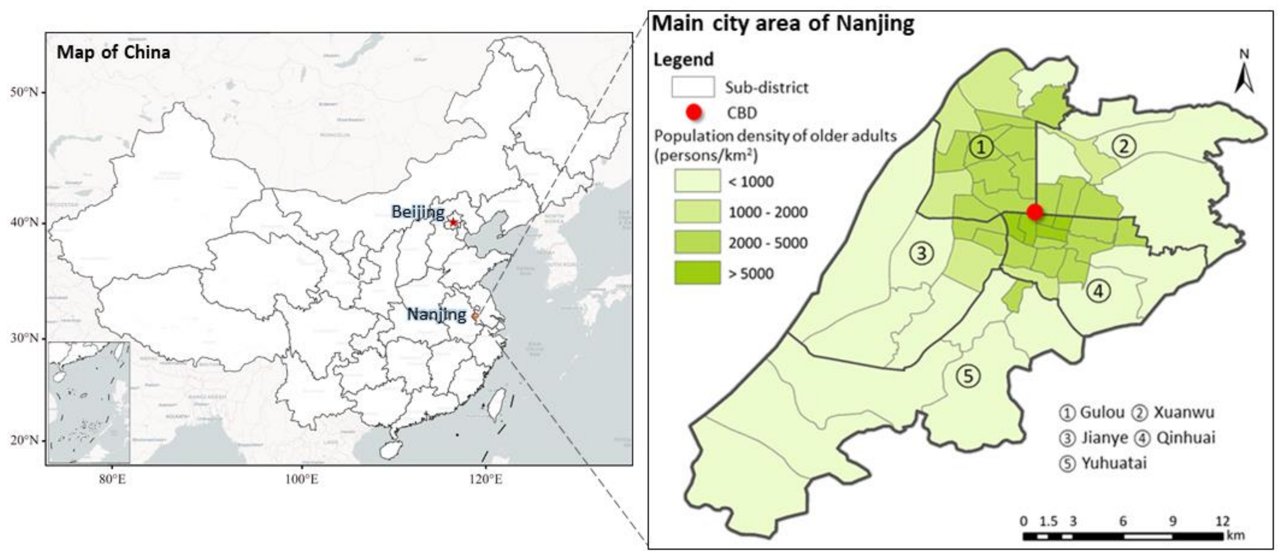


Figure 1. Map of the study area in Nanjing

The survey was carried out by the Nanjing Transport Bureau via face-to-face interviews in respondents' homes. Participants were asked to fill in a structured questionnaire which collected individual socio-demographic and travel information (e.g. start and end time, mode choice, and trip purpose). Travel diaries were used to record information about trips made during a designated 24-hour period on a typical day – Wednesday 30th October, 2013. A sub-district was used as the stratum of the survey. Individuals were randomly selected from each of the 49 sub-districts. To facilitate the representativeness of the sample, people residing in each stratum were contacted via computer-aided random-digit-dialling phone calls. These recruitment calls were made by the staff members of sub-district offices on 28th and 29th October, 2013. 5,562 residents agreed to participate in the survey, of which 5,172 provided complete answers. The respondents' residential addresses were geocoded on the map. In our analyses, we focused on older participants who were 60 or older, resulting in a sample size of 702 respondents. Table 1 presents the sample profile. A high proportion (48.1%) of respondents lived in medium-income households. The majority (64.0%) had no access to a car and 71.2% owned at least one bicycle in their household. A high proportion of respondents (85.6%) had a public transport pass which allows them to travel at reduced prices, whereas only 8.7% reported holding a driving licence. With respect to travel behaviour, the mean daily walking time of the older adults in the sample was 40.2 minutes. The spatial distribution of walking time is displayed in Figure 2 (following an interpolation procedure using the inverse distance weighting technique). The intensity of walking was relatively low in peripheral areas, with a minimum walking time of 20.5 minutes. The longest amount of time spent walking – a total of 199.1 minutes on the reference travel day – was reported in the Gulou District. We then employed a Global Moran's I test to examine correlations between nearby observations and the spatial pattern of walking time. The null hypothesis is that the data are spatially randomised (Fotheringham et al., 2002; Kim et al., 2019). The test gave a Moran's I Index of 0.75 with a z-score of 22.38, rejecting the null hypothesis. This indicates that older adults' walking behaviours are spatially clustered rather than evenly distributed over space.

Table 1. Walking outcome and built environment variables (N = 702)

	Variable	**Description**	**Frequency**	**Percentage**
Socio-demographics	Household income	High annual household income (> 150,000 RMB)	152	21.7%
		Medium annual household income (50,000–150,000 RMB)	338	48.1%
		Low annual household income (< 50,000 RMB)	212	30.2%
	Car ownership	Having a car in the household	253	36.0%
	Bicycle ownership	Having a bicycle in the household	500	71.2%
	Gender	Male	381	54.3%
	Education level	Higher educated respondent	91	13.0%
		Medium educated respondent	287	40.9%
		Lower educated respondent	324	46.1%
	Driving licence holding	Holding a driving licence	61	8.7%
	Public transport pass availability	Having a public transport pass entitling them to travel concessions	601	85.6%
	Variable	Description	Mean	SD
Built environment	Population density	Total number of residential population/Total built-up area in a buffer zone (persons/1000m^2)	10.75	12.37
	Land use mix	Land use diversity index measured by equation (1)	0.61	0.14
	Street connectivity	Total length of pavements/Total built-up area in a buffer zone (km/km^2)	3.72	4.36
	Number of bus stops	Number of bus stops in a buffer zone	5.02	2.84
	Number of bike-sharing stations	Number of bike-sharing stations in a buffer zone	4.03	2.89
	Distance to the nearest square/park	Distance to the nearest square/park in a neighbourhood vicinity (km)	1.50	0.83
	Distance to the nearest card/chess room	Distance to the nearest card/chess room in a neighbourhood vicinity (km)	0.61	0.48
Travel behaviour	Walking time	Total amount of time spent on walking trips on the reference travel day (minutes)	40.2	49.7

Note: SD = standard deviation.

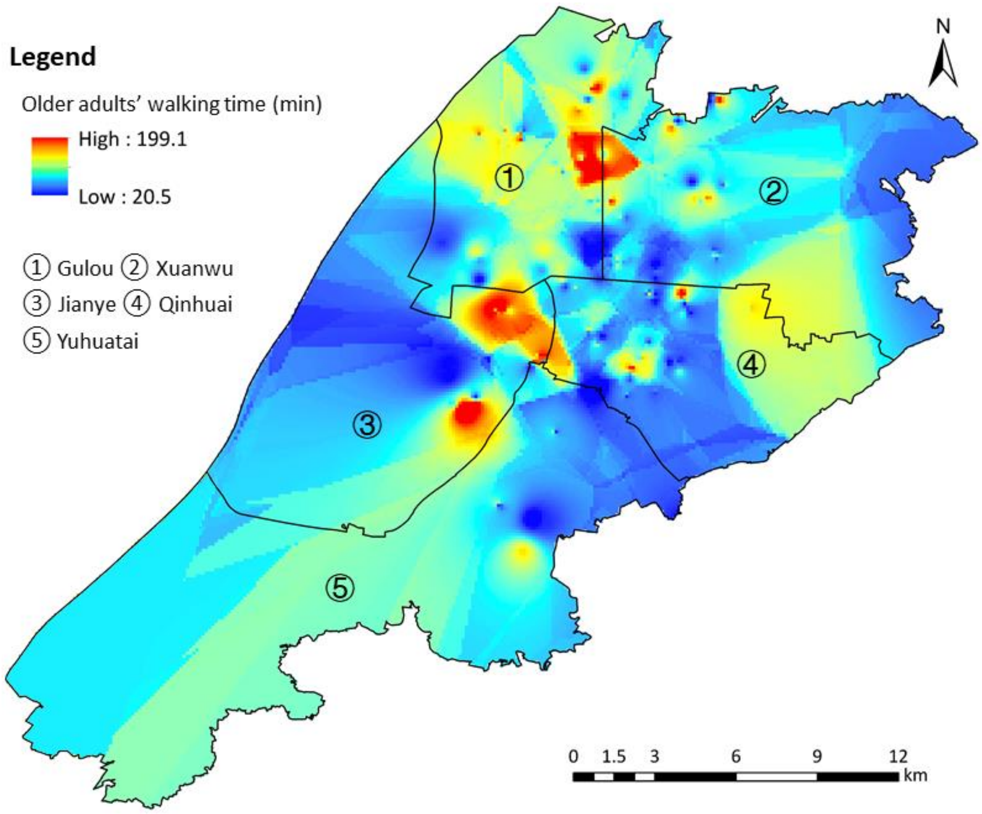


Figure 2. Map view of the daily time spent walking by older adults

Built environment data were sourced from the Nanjing Urban GIS Database. Seven built environment attributes that characterise the residential neighbourhood were calculated (see Table 1). These attributes were selected based on and developed from the existing literature on this topic (see Leung et al., 2018; Moniruzzaman et al., 2013; Yang et al., 2019). They are: (1) population density; (2) land use mix – this measure considers five types of land use: residential, commercial, educational, entertainment and public services. It measures the evenness of distribution of different types of land use and is calculated as follows:

$$H = -(\sum_{i=1}^{n} p_i * ln(p_i))/ln\,(n) \quad (1)$$

where H represents the land use mix score (ranging from 0 (complete dominance of one type of land use) to 1 (all types of land use are equally distributed)), p_i corresponds to the proportion of the i^{th} land use, and n is the number of land use types; (3) street connectivity – a measure of walkability – is computed as the density of pavements (Hou, 2019); (4) number of bus stops; (5) number of bike-sharing stations; (6) distance to the nearest square/park; and (7) distance to the nearest card/chess room room.[1]

[1] Chinese socio-cultural norms place a lot of emphasis on recreational activities for older people. It is customary for older people in China to regularly engage in a range of 'passive' recreational activities (Liu et al., 2008), for instance, public square dancing, talking with neighbours or friends, and playing cards, chess, and *mahjong*. Accordingly, the provision of a square/park or a card/chess room is likely to influence older adults' activity-travel pattern in the Chinese context.

These built environment attributes were assessed within a 500-metre buffer zone (Cerin et al., 2017) around respondents' residences.[2] Distances were calculated based on the shortest route along the street network. Table 1 presents the descriptive statistics for the built environment characteristics. The relatively high mean population density of 10.75 persons/1000m^2 implies that respondents largely lived in compact urban neighbourhoods. The mean land use mix score was 0.61 and the mean street connectivity was 3.72 km/km^2. Generally, the neighbourhoods had good access to public transport with an average of 5 bus stops and 4 bike-sharing stations.

3.2. Spatial modelling

A geographically weighted regression (GWR) model was employed to investigate spatially varying relationships. It extends conventional regression models by allowing coefficients to vary over space (Fotheringham et al., 2002). The GWR model was chosen because the result is not affected by the specification of a zoning system or by edge effects, and the local parameter estimates yielded could readily be visualised to reveal spatial variations (Blainey, 2001). The local effects of the built environment were estimated for each respondent based on the neighbourhood characteristics. A distance-based weighting scheme was used to ensure that data from close observations were given larger weights than data from more distant observations. GWR is a widely employed modelling technique which allows the spatial heterogeneity of relationships to be captured (Du and Mulley, 2006; Nowrouzian and Srinivasan, 2013; Yang et al., 2020).

In this study, the individual socio-demographics listed in Table 1 were considered as covariates in the model, because they are associated with older adults' walking (Böcker et al., 2017; Moniruzzaman et al., 2013). In addition, we tested the geographical variability of the coefficients of the GWR to assess the significance level of spatial non-stationarity (Nakaya et al., 2009). The Diff of Criterion (AICc) values for the socio-demographic variables showed no essential differences. Thus, they are specified as global variables. As a result, we built a semiparametric GWR model (i.e. spatial heterogeneity exists only for built environment effects while socio-demographic effects are unvarying), which takes the following form:

$$y_i = \sum_k \alpha_k(u_i, v_i)x_{ik} + \sum_m r_m x_{im} + \varepsilon_i \quad (2)$$

where y_i denotes the amount of walking time at point i, (u_i, v_i) refers to the coordinates of the i^{th} point in space, $\alpha_k(u_i, v_i)$ represents the local regression parameters associated with built environment attributes at point i, x_{ik} is the value of the k^{th} built environment attribute at point i, r_m represents the regression parameters – assumed not to vary by location – associated with socio-demographic variable x_{im}, and ε_i is the error term.

A spatial weighting function and a spatial kernel are required for model calibration. In this research, a Gaussian weighting function was used:

[2] Neighbourhood environmental attributes within 500-m from place of residence appear to be strong predictors of physical activity (including active travel) for older adults (Cerin et al., 2017).

$$w_{ij} = exp\ [-0.5\left(\frac{d_{ij}}{b}\right)^2] \quad (3)$$

where w_{ij} is the weight for data point j for estimating the coefficient at point i; d_{ij} is the distance between points i and j; and b is the kernel bandwidth. We used an adaptive kernel given that the regression points – i.e. respondents' places of residence – were irregularly distributed over space. An adaptive kernel ensures that each local regression has enough regression points. The kernel of the bandwidth is determined by minimising the corrected Akaike Information Criterion (AICc).

Before building the GWR model, we performed a variance inflation factor (VIF) analysis to detect possible multicollinearity between the explanatory variables. All the socio-demographics and built environment attributes in Table 1 have a VIF value of less than five – a threshold for excluding variables (Craney and Surles, 2002) – and thus are retained in the final model. The results show that an adaptive kernel consisting of 53 nearest neighbours for local regression produces the best result, as it offers the minimum AICc. Local coefficients are then interpolated to create continuous raster grids of spatial variations in the relationships. All analyses were carried out with MGWR 2.2 (Oshan et al., 2019) and ArcGIS 10.2 (ESRI Inc., USA).

4. Results and discussion

4.1. Delineating spatial heterogeneity

In Table 2, the range of local coefficients obtained through the GWR models indicates that the relationship between the built environment and walking among older adults varies over space. These variations in terms of either parameter sign or magnitude ascertain the spatial heterogeneity of relationships. By and large, we observed that all the built environment attributes, except for distance to the nearest square/park, are associated with an increase in walking time, indicated by the mean value of the GWR coefficients. The results showed that population density and land use mix exert both positive and negative influences. A comparison with the global (ordinary least square) regression model suggests that the GWR model produces a superior performance. The GWR model produces a higher R^2, a lower AICc value, and a smaller residual sum of squares. The global model does not consider the geographical position of respondents and thus produces an inadequate representation of the local relationships (Fotheringham et al., 2002). In statistical terms, we used the Moran's I Index to examine the autocorrelation between residuals of the global model. The null hypothesis is rejected – with a Moran's I Index of 0.457 and a z-score of 21.38 – which shows the existence of spatial autocorrelation. This result further supports the validity of GWR models.

The emphasis here is on discussing the spatially varying built environment effects by mapping estimated coefficients and t-statistics, as shown in Figure 3. We observed that spatial heterogeneity affects all the relationships, with nuances in the significance level, parameter magnitude and sign reversals, depending on locations. In general, insignificant relationships mainly occur where data points are sparse, e.g. the south-western part of the study area. This is particularly evident in Figures 3a, 3b, and 3f. This may be due to the fact that these areas show less variation between built environment attributes. A lack of variation in the explanatory variables means reduced standard errors of the coefficients and may therefore lead to insignificant relationships.

Table 2. Estimation results of the GWR model

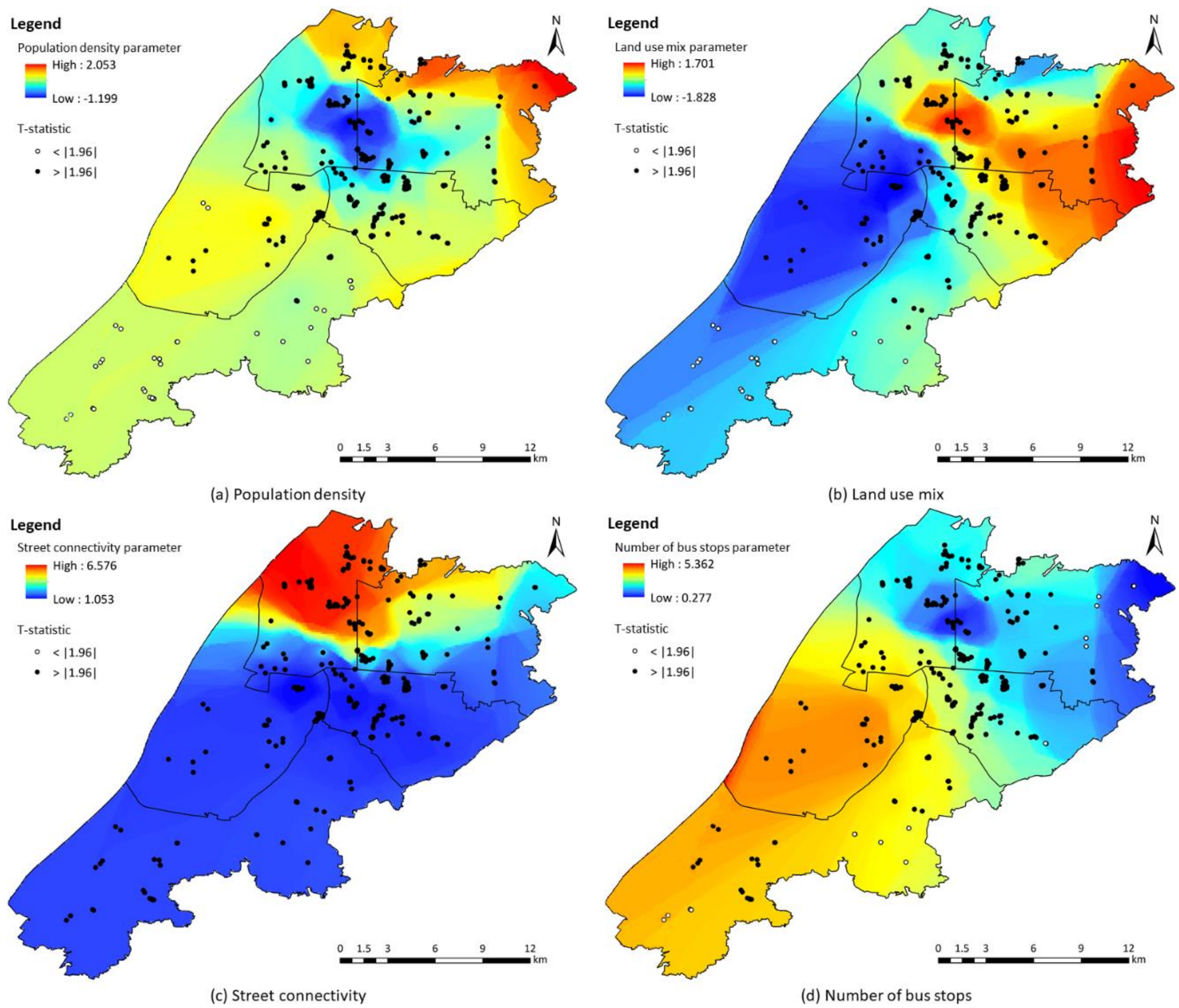
Variable	GWR model			Global model	
	Distribution of coefficients			Coefficient	T-statistic
	Mean	Min	Max		
Population density	1.306	-1.199	2.053	1.393	1.974
Land use mix	0.960	-1.828	1.701	1.019	2.191
Street connectivity	3.950	1.053	6.576	4.064	2.451
Number of bus stops	3.052	0.277	5.362	3.033	2.543
Number of bike-sharing stations	2.015	0.135	4.210	2.251	2.385
Distance to the nearest square/park	-2.944	-4.258	-0.718	-2.719	-3.326
Distance to the nearest card/chess room	3.595	0.723	5.166	3.788	2.037
R^2	0.589			0.407	
Adjusted R^2	0.426			0.315	
AICc	1576.000			1648.000	
Residual sum of squares	484.996			564.568	

Note: T-statistics for coefficients in the GWR model are not shown as they vary by location.

Increasing population density or land use mix is associated with highly contrasting variations in the likelihood of walking. While the relationship is positive in some areas, it is negative elsewhere. Specifically, the relationship between population density and walking close to the north CBD is negative, which contrasts with the rest of the study area (Figure 3a). Walking is positively associated with land use mix except in areas located in the west (Figure 3b). These mixed results may be attributed to the curvilinear effects of the built environment on walking (Christiansen et al., 2016; Perchoux et al., 2019). A higher population density creates a critical mass of pedestrians – people walk more, more road space and infrastructure will be allocated to pedestrians, and walking will become more established and pleasant. However, when the population density reaches a high level in some places (e.g. CBD), it will have a negative impact on walking. This might relate to the higher risk of sustaining injuries in crowded places, in particular for older people, some of whom may have reduced physical capabilities. In terms of the land use mix relationship, a greater diversity of land use offers opportunities for local activities, which is conducive to walking (Kamruzzaman et al., 2016). Nonetheless, older adults in highly mixed areas may chain multiple trips in a single journey due to easy access to destinations and services, thereby reducing the amount of time they spend walking.

The local effects of street connectivity on walking are significantly positive over the entire study area (Figure 3c). The distribution of coefficients demonstrates a southward decreasing trend. Better street connectivity facilitates walking through the provision of more (direct) routes within the neighbourhood and shorter distances to destinations. In terms of the relationship between walking and access to public transport (i.e. the number of bus stops and the number of bike-sharing stations in the neighbourhood), Figures 3d and 3e show that the parameters are positive everywhere. The distribution of coefficient estimates for the number of bus stops indicates that the largest values are in the Jianye District, while the trend decreases moving towards north-eastern neighbourhoods (Figure 3d). On the other hand, coefficient estimates for the number of bike-sharing stations are comparably greater in the north, with the effect being particularly pronounced in the Xuanwu District. Travelling by public transport is always coupled with walking to and from bus stops/bike stations (Freeland et al., 2013) and walking comprises a proportion of most public transport trips. Moreover, neighbourhoods with better public transport accessibility may facilitate walking among non-users of public transport. For instance, a large share of people walking to public transport facilities can foster a pedestrian-friendly environment and the idea that walking can be considered as an important way of travelling (Forsyth et al., 2007).

The spatial pattern of relationships reveals differences between the distance to a square/park and the distance to a card/chess room. The former type of amenity displays a negative relationship, but the latter shows a positive outcome. Living farther from a square/park appears to discourage walking among older adults with the coefficient varying from -4.258 to -0.718 (Figure 3f). For the distance to a card/chess room, the strongest relationship is found in the most easterly area (Figure 3g). Every one-unit increase in distance is associated with an approximately 5.2-minute increase in walking time. It is noteworthy that the provision of a card/chess room in the nearby vicinity appears to constitute a significant barrier to walking. The potential rationale is that card/chess rooms tend to appeal more to senior citizens and they spend more time engaging in such activities, which reduces the amount of time allocated to walking per day.



(a) Population density

(b) Land use mix

(c) Street connectivity

(d) Number of bus stops

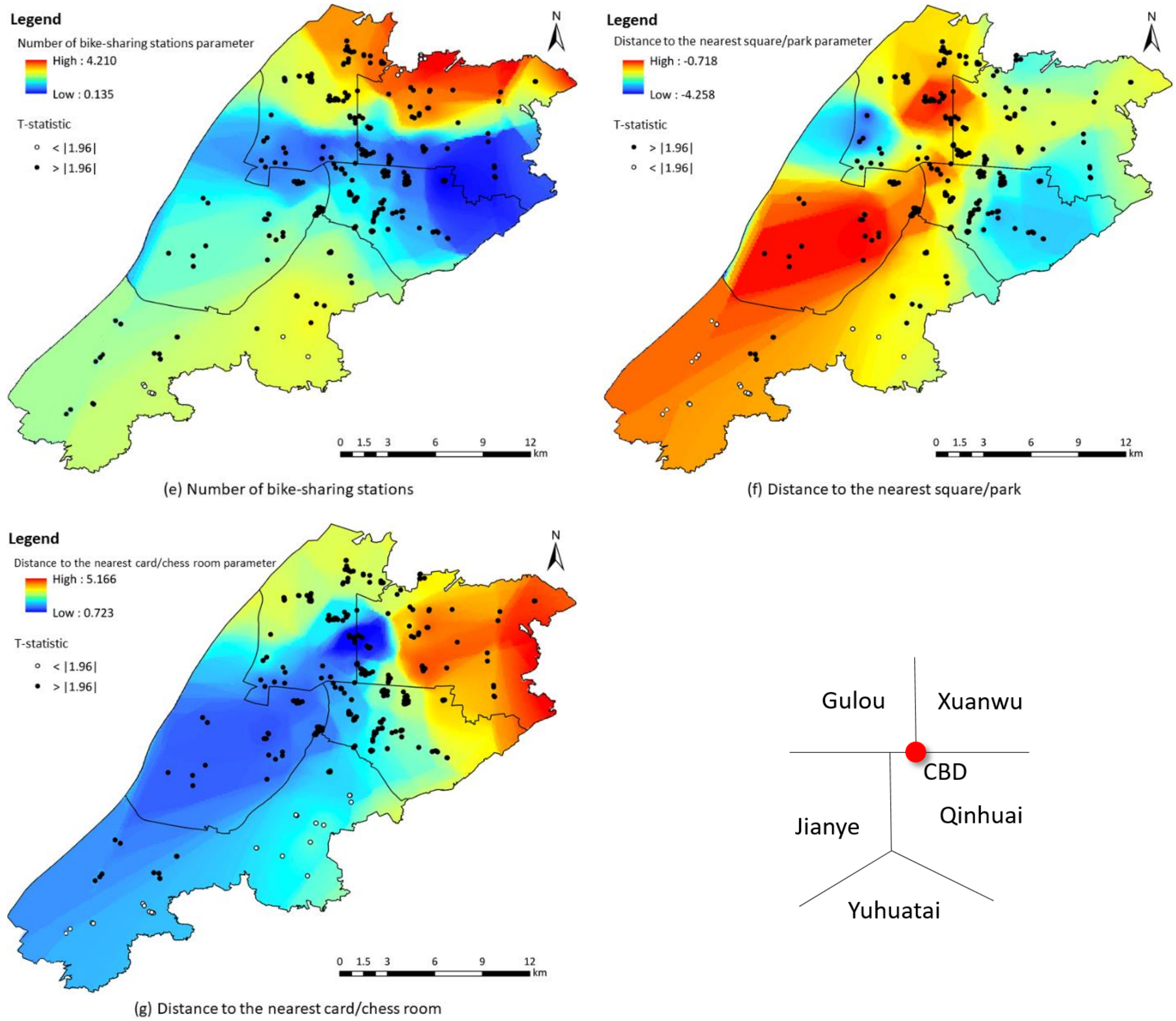


Figure 3. Map results of GWR parameter estimates

4.2. Characterising local contexts of relationships

In this section we attempt to explain what characterises the local contexts where the relationship between the built environment and walking varies. A K-means clustering method based on local relationships – i.e. GWR model coefficients – was used. The K-means algorithm partitioned the observations into several non-overlapping and distinct clusters. The optimal number of clusters is determined a priori in an iterative way according to the silhouette value (Rousseeuw, 1987). A result of four clusters yields the highest silhouette value at 0.68. These clusters are supposed to represent four local contexts in which the effects of the built environment on older adults' walking are as distinguishable as possible.

We mapped these clusters as shown in Figure 4. The four clusters are spatially distributed across the main city: Clusters A and C are concentrated around the city centre, Cluster B is mainly in the north, and Cluster D covers the southern area. Table 3 reveals that there are significant differences in individuals' socio-demographics and/or built environment characteristics across clusters. Comparing Clusters A and C using two-sample t-test analyses, we found that these two clusters have insignificant differences in relation to all the built environment attributes (except for distance to the nearest square/park). This shows that the discriminative variables between them are socio-demographics. This finding suggests that socio-demographic variables are likely to be important moderators in the relationship between the built environment and older adults' walking. The other interesting point is the result revealed by the comparison of Clusters B and C. The discriminative variables are those relating to the built environment where the socio-demographics are relatively similar. Clusters B and C are located in strongly contrasting urban areas (hence they have different built environment attributes), as represented by the small p-values. This suggests that the built environment itself could play an important role in walking among older adults.

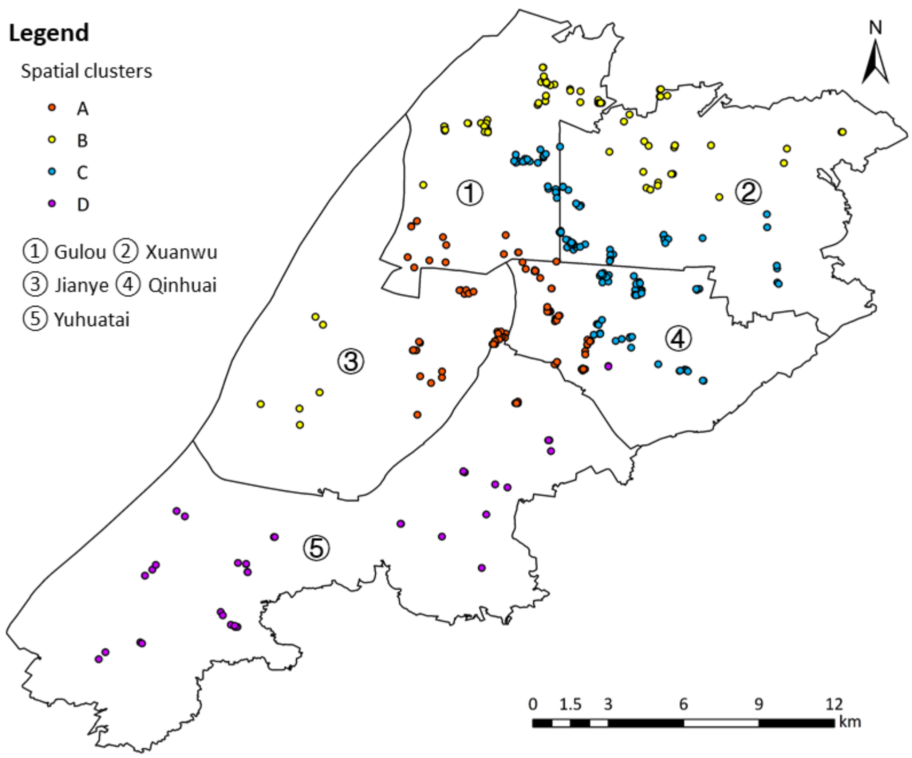


Figure 4. Spatial clusters from GWR results

Table 3. Comparison of the contextual variables for spatial clusters (N_A=187, N_B=193, N_C=224, N_D=98)

		Cluster A vs B	Cluster A vs C	Cluster A vs D	Cluster B vs C	Cluster B vs D	Cluster C vs D
Socio-demographics	Household income	grey	grey	grey		grey	grey
	Car ownership	grey	grey			grey	grey
	Bicycle ownership		grey	grey		grey	grey
	Gender		grey	grey			grey
	Education level	grey	grey			grey	grey
	Driving licence holding	grey	grey	grey			
	Public transport pass availability	grey				grey	
Built environment	Population density			grey	grey	grey	grey
	Land use mix	grey		grey	grey	grey	grey
	Street connectivity	grey		grey	grey		grey
	Number of bus stops	grey		grey	grey		grey
	Number of bike-sharing stations	grey		grey		grey	grey
	Distance to the nearest square/park	grey	grey	grey	grey	grey	grey
	Distance to the nearest card/chess room	grey			grey	grey	grey

Note: A grey cell indicates that the two-sample t-test analysis produces a p-value smaller than 0.05.

In general, the spatial clustering of relationships indicates that people living in adjacent places have a greater tendency to walk according to a similar pattern than individuals living farther away. This result is in line with Tobler's first law of geography (Tobler, 1970). Based on the characteristics of the clusters, we can make some theoretical and conceptual speculations about what spatially differentiates the associations between the built environment and walking among older adults. First, inhabitants residing in the same neighbourhoods tend to resemble each other in socio-demographic terms and thus exhibit similar walking trends. This resemblance refers to the notion of residential self-selection (Cheng et al., 2019d; Mokhtarian and Cao, 2008), indicating that people choose to live in certain neighbourhoods that match their travel and non-travel preferences. Social interactions developed inside the clusters may also make individuals tend to travel in similar ways. This implies that someone's behaviour may be affected by her/his neighbour's behaviour, through the mechanism of peer effects or travel socialisation (Haustein et al., 2009; Walker et al., 2011). Second, built environment attributes in the same neighbourhoods exert shared influences on local inhabitants, without the interaction of individuals living there. For example, older people living close to squares or parks are more likely to spend more time walking, regardless of the resemblance between individuals. This finding is compatible with the notion of environmental determinism (Lin et al., 2017; Subramanian et al., 2003), meaning that the built environment can play a dominant role in affecting travel behaviour.[3] The two mechanisms described above appear to concurrently explain the clustering pattern of the relationships. To put it another way, individual and environmental characteristics constantly interact to influence travel behaviour.

[3] Housing affordability is limited for many older people in Nanjing which constrains their residential choices. The high price of housing in the main city prevents some older people from realising their residential preferences, resulting in limited residential self-selection effects.

4.3. Policy implications

In planning practice, the effects of the built environment on older adults' travel behaviour should be assessed at a local scale. Therefore, it is important to locally tailor land use and transport policies to encourage walking. For instance, increasing street connectivity may have a stronger effect on walking in the northern area (covering most of the Gulou District) than in the rest of the study area (Figure 3c). A one-unit increase in street connectivity improves the level of walking by 6.6 minutes in the area farthest north. Increasing the number of bus stops – which is conducive to walking – would be more useful in the south-western area than the eastern area (Figure 3d). It also appears that some policies may have unexpected outcomes in certain places. For instance, densification in an already compact area (e.g. the north CBD in Figure 3a) may exert negative impacts on older adults' walking. Excessively mixed land use could also be a barrier to increasing walking time (e.g. in the west of our study area, Figure 3b). The provision of recreational facilities needs to be implemented with caution. Proximity to a card/chess room leads to a reduction in walking time (Figure 3g) and is more likely to result in a sedentary lifestyle for older adults (although it may offer some social and leisure benefits).

Our findings can assist in prioritising some places in terms of policy interventions which encourage walking among older adults. Figure 2 illustrates that there are significant differences in walking level, i.e. some locations show a lower level of walking than others. In the western Jianye District, walking intensity is low (Figure 2), while Figure 3 shows that there are significantly positive relationships for street connectivity, number of bus stops, and presence of a square/park. This suggests that these places may be a focused target for encouraging walking by improving street connectivity, access to public transport, and provision of public venues for walking (e.g. parks, squares, or plazas). The south-eastern area shows a low level of walking and positive associations with population density and land use mix. This could inform policy initiatives in terms of densification and mixed land use development. Such locally nuanced prioritisation is not only more efficient than global-level interventions for supporting walking, but also ensures improved cost-effectiveness in planning practice.

5. Conclusions

This study investigated spatial differentiation with respect to how the built environment is associated with walking among older adults using data from the 2013 Nanjing Household Travel Survey. A geographically weighted regression (GWR) model was employed to investigate the spatial heterogeneity, while controlling for socio-demographics. The comparison with the global model demonstrates the validity of the GWR model, which considers the spatial non-stationary process that operates within the data. In this research, we found that the built environment is strongly associated with the time that older adults spend walking, and these relationships vary over space. This primary evidence on spatial heterogeneity reveals that associations between land use and travel behaviour should be assessed at a local level and thus strongly favours place-based analyses and interventions.

Two spatial patterns of associations were observed in this research. The first is the contrast between the centre and the periphery. The bulk of the insignificant relationships are located on the south-western periphery, where respondents are sparse. The second observation relates to the differences in built environment effects in terms of parameter magnitude and sign over space. The overall influences of the built environment appear to be stronger in the northern and eastern regions of the study area. We showed that street connectivity, number of bus stops, number of bike-sharing stations, and distance to the nearest card/chess room are positively associated with walking time throughout most of the area, which is congruent with similar studies (e.g. Barnes et al., 2016; Kemperman and Timmermans, 2009; Liao et al., 2018; Suminski et al., 2005). However, increased distance to a square/park corresponds to shorter walking time. Population density and land use mix show a reverse directionality of influences across locations, i.e. both positive and negative effects. Therefore, there should be an optimal range of compactness and land use mixture which can be regarded as sustainable. Beyond a certain threshold, high-density or mixed-use urban developments could be detrimental to active travel among older people, and even to their quality of life.

The major finding of this research is the delineation of places with heterogeneous associations between the built environment and older adults' walking. The spatial heterogeneity of relationships implies that, from a practical perspective, land use and transport interventions should follow the spatial pattern of relationships which would improve policy efficiency. In other words, any interventions designed to increase walking should be tailored to local conditions. The GWR technique with readily interpretable maps would be a useful instrument to guide locally tailored planning practice. On the other hand, from a theoretical perspective, our results imply that local contexts influence the spatial heterogeneity of relationships between the built environment and walking. These contextual effects may be due to the specific intrinsic characteristics of individuals (i.e. socio-economic level) and environmental attributes (i.e. physical features of the neighbourhood).

Several research avenues can be anticipated based on this study. First, future studies on the effect of the built environment on travel behaviour, for population groups other than older adults, and modes of travel other than walking, should also take this spatial heterogeneity into account. Second, the cross-sectional investigation conducted in this study makes it difficult to infer that there is a causal pathway between the built environment and walking. More qualitative and quantitative research (e.g. longitudinal or quasi-experimental investigations) is needed to examine the issue of causality, after controlling for residential self-selection effects (Handy et al., 2006). Third, additional moderating variables would be likely to improve the robustness of the GWR models. Therefore, future studies could include more environmental and individual variables, e.g. weather (Hjorthol, 2013), pedestrian infrastructure (Moniruzzaman and Páez, 2016), perceptions of the built environment (Li et al., 2019), and capabilities and functionings (Cao and Hickman, 2019). Those variables would provide further insights into the correlates of older adults' walking. Despite these limitations, this study is useful in revealing and explaining the spatially varying impacts of the built environment on walking among older adults. These findings could not only help to develop more effective and locally adapted planning interventions for encouraging active ageing, but also advance the understanding of associations between land use and travel behaviour.

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