Highlights

- We present a framework that integrates logistic geographically weighted regression (GWR) with spatial accessibility measures to explain children's walking behaviour.
- The framework focuses on the varying relationship between different purposes of walking (recreational and transportation) among children and urban form factors as well as socio-economic status (SES).
- The walkability framework is applied to the Asian part of Istanbul, Turkey.
- Planners and policy makers can use this framework to provide targeted interventions rather than blanket solutions for the design of neighbourhoods in promoting active lifestyles among children.

Abstract

This study aims to examine associations between urban form factors generally, and street network configuration in particular, and walking for different purposes among children in Istanbul, Turkey. Parents of randomly selected students (ages 12-16) at 20 middle schools (N=917) completed questionnaires about their socio-economic characteristics and the frequency of their children's walking for recreational and for transportation purposes in their neighbourhood during a typical day. The environment around 400 meters of participants' homes was evaluated through GIS-based parcel-level land-use data and segment-based street connectivity measures calculated using space syntax techniques. Logistic geographically weighted regression models were estimated to measure the desired associations while adjusting for socio-economic characteristics. Results demonstrate a marginal association between urban form measures and walking behaviour but only in certain peripheral parts of the city. More importantly, increased directional accessibility, which identifies the extent to which more street length is accessible within few direction changes, is associated with higher odds of recreational walking in particular areas where a strong differentiation between scales of street connectivity structure is evident such as a supergrid of primary roads with inserted organic local streets. In addition, children residing in neighbourhoods with reduced residential density and increased commercial and recreational activities are more likely to walk for transportation purposes. The findings of this study demonstrate that the one-size-fits-all approach may not effectively encourage walking. Urban areas tend to have varying qualities that need to be handled uniquely, and therefore targeted rather than blanket interventions regarding the design of neighbourhoods around schools and homes may be beneficial in supporting walking behaviour of children.

Keywords: street network configuration, home environment, transportation walking, recreational walking, geographically weighted analysis, Istanbul

1. Introduction

Walking as a significant component of physical activity provides related benefits including but not limited to reducing traffic, increasing air quality, providing physical activity, and improving public health and associatively has become one of the major topics of urban studies. Although a growing body of research has examined environmental correlates of adults' walking behaviour, research exploring the factors associated with children's walking is still limited (Giles-Corti et al., 2009; Spinney and Millward, 2011). This study is directly related to national and international concerns regarding decreased levels of physical activity and increased prevalence of obesity among children (Healthy Eating and Active Living Program in Turkey, 2009; US Department of Health and Human Services, 2010). Promoting walking as part of children's everyday life is pertinent (Carlin et al., 2016) since it is a remarkable factor in the fight against obesity and obesity-related chronic diseases (Lorenc et al., 2008). Furthermore, studies show that healthy behaviours learned in childhood have significant effects on adult behaviours (Schlossberg et al., 2006).

Studies investigating the specific environmental correlates of children's active travel follow two lines of inquiry. The first group of studies focuses on street-level factors affecting children's active commuting (Rothman et al., 2014). Research in health and urban design that investigates the environmental correlates of walking has documented associations between street-level design and pedestrian activity. Most of the emphasis is placed on the physical qualities and condition of individual streets. The main theme of this research is that the availability and conditions of sidewalks (Muraleetharan and Hagiwara, 2007; Rodríguez et al., 2015) along with as the presence of controlled crossings and signals (Boarnet et al., 2005), attractive landscaping, and tree cover (Agrawal et al., 2008; Cao et al., 2007; Larsen et al., 2009) are positively associated with children's active commuting. Additionally, aesthetic or safety features, such as cleanliness, interesting sights, and architecture (Appleyard, 1982; Gehl, 2011) have been shown to encourage walking among adults and children. Evaluating local attributes of the physical environment is clearly important in creating neighbourhoods that are supportive of walking. However, walking is a context-

dependent activity that requires people to navigate *through* spaces, not *in* spaces. Thus, investigating the local qualities of the individual street without considering the global characteristics of the surrounding urban form would not be sufficient to explain walking behaviour.

A second body of research in transportation and planning has focused on urban form aspects of walkability, characterized in terms of land-use patterns and street network connectivity. To date, studies of the built environment's impact on walking behaviour have focused on land-use diversity and densities. Land-use diversity, or the distance between different types of land-uses, such as residential and retail uses, is measured in terms of the number of available destinations within walking range. Dowda and colleges (2007) discovered that commercial physical activity facilities, such as dance studios and youth organizations, nearby homes are essential to the accumulation of physical activity (among adolescent girls). It is argued that commingling of a variety of activities, such as residences, shops, restaurants, and offices, supports the motivation to walk (Cervero, 2002; Ding et al., 2011; Larsen et al., 2009; Rodríguez and Joo, 2004; Rodríguez et al., 2009). Current research (Borgers and Timmermans, 1986; Nagel et al., 2008) shows that diverse land-use patterns around the school are associated with higher rates of walking to school (McMillan, 2007). Walking occurs within the constraints of distance and time; hence, the number of existing destinations within walking range is likely to influence walking behaviours. Previous research has shown that increased proximity to destinations from origins, such as homes and schools, is associated with increased odds of walking (Giles-Corti et al., 2013; Handy and Clifton, 2001; Hirsch et al., 2013; Lee et al., 2013), because the availability of destinations within neighbourhoods offers the possibility to link trips en route.

There is a growing body of research on the role of street networks and their layouts. Proportion, number, and length of walk trips are shown to be positively related to more connected street networks measured through reduced size of street blocks or the presence of a fine-grained urban network of densely interconnected streets (Kerr et al., 2007; Moudon et al., 2006; Panter et al., 2010; Voorhees et al., 2010). Despite the recognition in planning and urban

design research of the significance of street network connectivity in promoting physical activity, the effect of street network configuration on active travel remains ambiguous. One challenge is the lack of measures that can systematically evaluate the spatial structure of urban street networks at various scales. Spatial structure may be defined as the collection of streets and street segments through certain alignments and hierarchies. The significance of spatial structure as a crucial correlate of walking has been highlighted within space syntax theory. Earlier research suggests that streets that are accessible from their surroundings with fewer direction changes tend to attract higher densities of pedestrian flows (Baran et al., 2008; Hillier et al., 1993; Hillier and Raford, 2010; Peponis et al., 1997). Related studies have shown that street network configuration is significantly related to recreational (Lee and Moudon, 2006a) as well as transportation (Ozbil and Peponis, 2012) walking behaviours. Recent research using syntactic measures have identified the significance of the foreground structure of cities, defined by the linear continuity of few streets generating a distinctive pattern of a supergrid, in creating a connected street network (Haq and Berhie, 2018; Peponis et al., 2015; Serra and Hillier, 2017). These studies argue that this supergrid acts as a primary skeleton for the whole network and affords connections to all parts within the system.

However, studies using space syntax measures to explain walkability have mostly analysed data at the global level (OLS or logistic regression), regarding the relationship between urban form factors and walking as stationary. Contrarily, differences in physical/geographic space are essential for the underlying theory and methodology of space syntax. To the knowledge of the authors, only one study (Yao and Karimi, 2015) has so far applied a local regression approach in space syntax analysis by considering the heterogeneous structure of space. Using mixed, geographically weighted regression (MGWR) and space syntax measurements to determine the association between spatial configuration and property values in Shanghai, this study revealed the relationship between urban configurational accessibilities and the spatially varied house price pattern with a proper consideration of spatial heterogeneity. So far no study related to walkability has been conducted

that applied a local regression approach with space syntax measurements to determine the varying nature of walking behaviour.

This study contributes to the literature by presenting a methodological modeling framework that integrates logistic geographically weighted regression (GWR) with spatial accessibility measures. This paper focuses on two urban form factors: land-use around the home, measured using GIS-based parcel-level data, and street network connectivity, measured using space syntax measures. The primary aim is to determine the varying relationship between different purposes of walking (recreational and transportation) among children and urban form factors, considering socioeconomic characteristics. A plethora of studies have focused on walking categorized by various purposes, such as leisure/recreational vs. transportation, and their correlates (Mitra et al., 2010; Pikora et al., 2003; Rajamani et al., 2003; Yang and Diez-Roux, 2012). Yet, existing research indicates that specific environmental attributes associated with different purposes of walking tend to differ (Troped et al., 2003). Thus, failure to consider them separately may result in biased outcomes. In addition, since the majority of studies have investigated the environmental correlates of adults' active travel, research focused on understanding the factors related to children's active travel is limited (Giles-Corti et al., 2009). This research aims to fill this gap by employing a questionnaire that differentiates between walking for recreation and walking for transport purposes among children.

2. Methodology

2.1 Study Site

Data for this cross-sectional study were drawn from questionnaires administered in 20 middle schools located in Istanbul, Turkey, in 5 districts chosen for their variability in education levels and spatial structure of street networks (Figure 1). Kadıköy and Üsküdar are central-city districts, whereas Ataşehir and Kartal/Ümraniye are contemporary suburban and peripheral districts, respectively. This study focuses solely on the Anatolian (Asian) part of the city since different urban patterns dominate each continent. High-rise mass housing, service, and commercial land-uses dominate the European part,

whereas the Anatolian part reflects a mostly residential character. Although the selected areas represent a small cross-section of the city, they capture one-sixth of the entire population. The 2015 population rates of the study districts (the districts the selected schools fall into) are higher than the average population rates of 39 districts within the entire city as well as than that of the 14 districts located in the Anatolian part. Ümraniye has the highest population (688,347) whereas Ataşehir has the lowest (419,368). The average monthly income of districts Kadıköy, Üsküdar and Ataşehir are above the average monthly income of all districts within Istanbul and those within the Anatolian part, while that of Kartal and Ümraniye are marginally below those. In terms of education levels at the district scale, all the study districts have higher numbers of college and/or postgraduate degrees than the average education levels of all districts within the city and those within the Anatolian part. However, Kadıköy has the highest education level whereas Ümraniye has the lowest among the study districts.

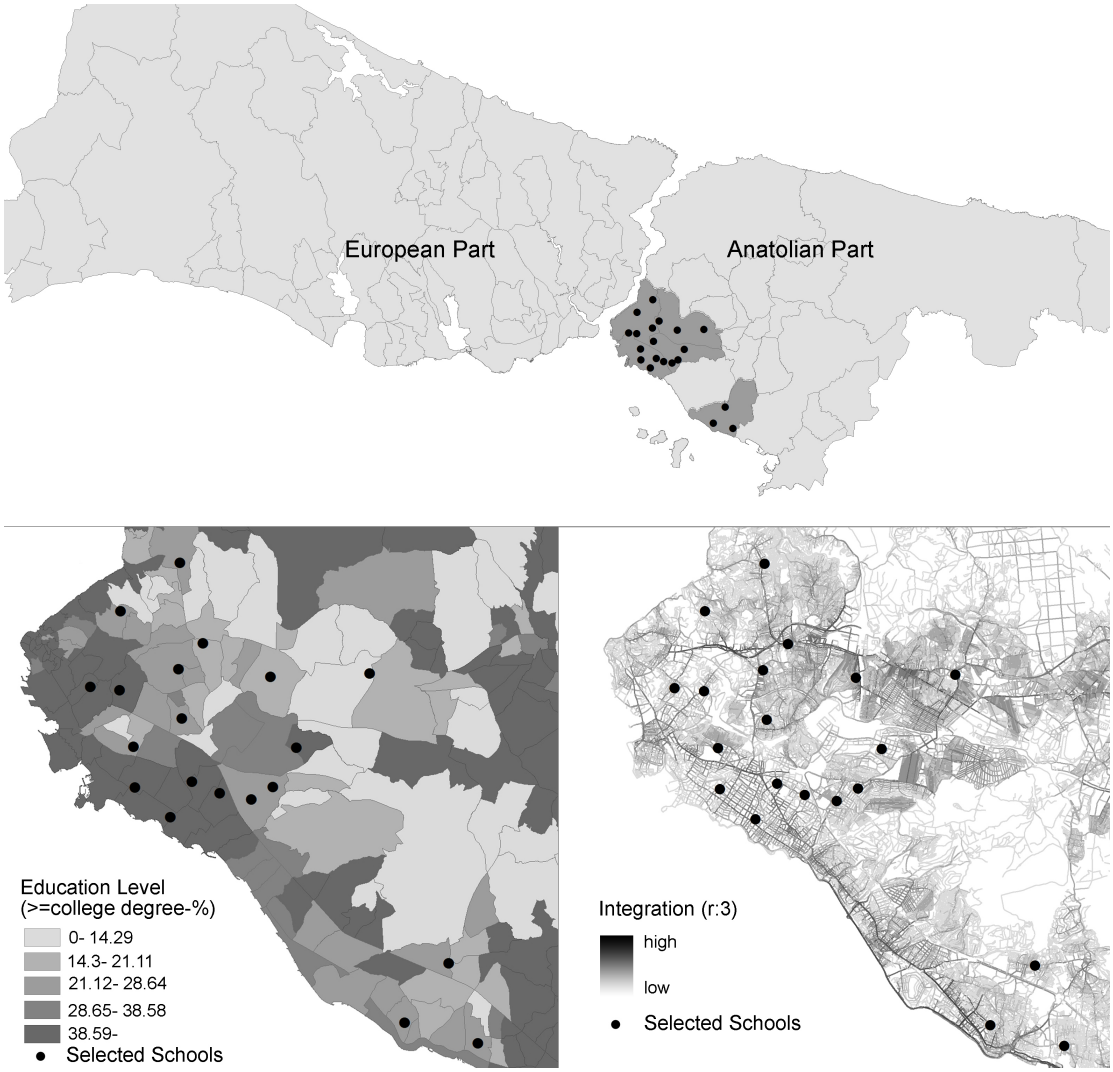


Figure 1. The location of selected schools mapped by education levels of districts and street network integration[1].

2.2 Participant Data

Parents of randomly selected students (ages 12–16) were asked to complete questionnaires between May and December of 2014 (N=1261). The final set of respondents were geocoded to a unique street address (N=917). Parents reported their child's main purposes for walking within their neighbourhood (e.g., walking for leisure, walking to/from school, etc.) as well as the frequency of recreational and transportation walking they did during a typical day in their

[1] Integration, which is similar to closeness centrality, measures how easy it is to access each space from all the others within the system.

neighbourhood. Ethical approval for the study was obtained from the National Ministry of Education and the host university's Research Ethics Committee.

2.3 Variables

2.3.1 Land-use Measures

Since 400 meters (a quarter mile) is prevalently used and recommended by the planning community as the walkability index around homes (APUDG, 2004; Azmi et al., 2012; Barton et al., 2003; McMillan, 2007; Olson, 2010; Perry, 1929), home environments (400-meter aerial buffers around the respondent) were evaluated using GIS-based measures. Parcel-level land-use densities were summarized for each buffer using 2014 GIS-based land-use data provided by the Municipality. Land-use was categorized into residential (single and family housing), commercial (retail, commercial, office, catering), and recreational (parks, playgrounds, and fields/wooded areas). The distribution of homes of participants around a selected school and land-use compositions within 400 meters of a selected home are shown in Figure 2. The linear distance of study participants from major activity/employment nodes was also measured and considered as a variable within the statistical analysis. This was created using the fishnet coverage in GIS to calculate the distance of homes to major retail, commercial and business nodes. In addition, a dichotomous "school district" variable was created to control for the distance of home to school. Participants residing within 400m. buffers of their schools were coded as 1; those living outside of 400m. buffers were coded as 0.

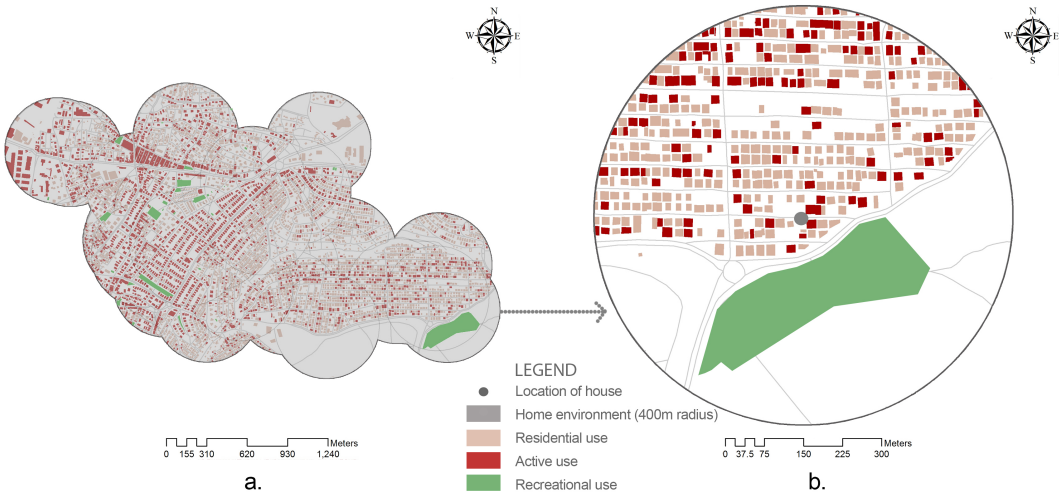


Figure 2. a) The distribution of homes within 1,600 meters of a selected school, and b) land-use compositions within 400 meters of a selected home.

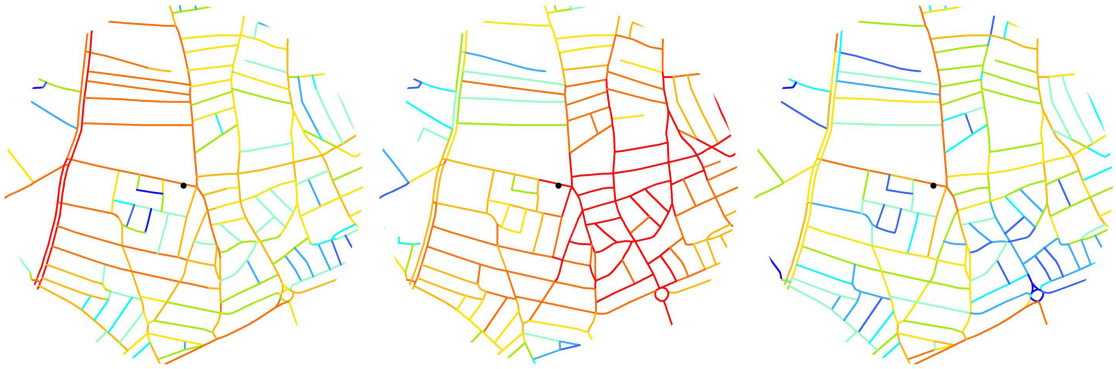
2.3.2 Street Network Measures

Street network connectivity is computed according to space syntax theory. Street network configuration within home environments was quantified using three different descriptors of the spatial structure of street networks based on the 2014 Streetmap provided by the Municipality. The street network map was revised so that highways and motorways, which do not provide access to pedestrians, were eliminated; and missing pedestrian pathways and lanes were added onto the map. Hence, the analysed map included a wide range of pedestrian-oriented routes. Segment Angular Analysis was conducted to calculate Integration, which measures how easy it is to access each space from all the others within the radius using the least angle measure of distance. This measure represents the *to* movement potential of the street segment (Hillier et al., 2012). Integration (radius 3)[2] was calculated to capture the local sub-centres within districts. The platform used to calculate Integration is Depthmap, developed by Turner (2001) and Varoudis (2012).

The street network configuration of the entire Anatolian part was also analysed using two parametric measures of connectivity: *metric reach* and *directional reach* (Peponis et al., 2008). In metric reach analysis, the density of street network is captured by measuring the total street length accessible from each

[2] Radius 3 is a local measure, which calculates the Integration values of each segment within 3 steps (change of segments) from the segment within the system.

street segment up to a parametrically specified metric distance threshold. Directional reach measures the total street length accessible from each street segment up to a certain number of direction changes, parametrically defined via a threshold angle. Metric reach was computed for a 400-meter walking distance threshold. Directional reach was computed for two direction changes subject to a 20° angle threshold. The 20° angle threshold was selected to ensure that the analysis captures street sinuosity. Computing directional reach for two direction changes measures the extent to which a street segment is embedded within the surrounding street network in terms of directional distance. Figure 3 illustrates Integration (r3), metric reach (400m) and directional reach (20°, 2-direction changes) respectively. The potency of these measures in explaining the distribution of pedestrian flows in urban settings and route choice among students has been demonstrated in the literature (Ozbil et al., 2016, 2015).



a. Integration (r:3) b. Metric Reach (400m) c. Directional Reach (20°, 2-direction changes)

Figure 3. The same street network configuration measured using three different configurational measures.

2.3.3 Socio-economic Measures

Since previous research has demonstrated the significance of socio-economic status (SES) in physical activity and walking levels of adolescents (D'Haese et al., 2014; De Meester et al., 2012), SES of both selected participants and neighbourhoods was considered as independent variables in the statistical analysis. The parents of selected children answered questions regarding their income (average monthly income), car ownership (number of cars owned by household) and education (the degree held by both the mother and the father).

A dichotomous “parental education” variable was calculated by coding participants whose at least one parent had a college degree or a higher degree as 1; the remaining as 0. To examine the associations of neighbourhood-level socio-economics, the neighbourhood-scale education level data were also accessed through the website http://www.mahallemistanbul.com/MahallemSEGE, which demonstrates the results of a quantitative study based on the neighbourhoods of Istanbul. Since this is the only data regarding the neighbourhood-level socio-economics of the city, the neighbourhood-scale income failed to be considered as a variable in the statistical analyses.

2.3.4 Transportation and Recreational Walking

Walking for transportation and/or recreation purposes was measured by 5-Likert type scale questions: walking always (5days/week), frequently (3-4 days/week), occasionally (1-2days/week), rarely (1d/week), and never (0day/week). One dichotomous dependent variable was developed for measuring transportation walking in line with literature (Moran et al., 2016; Taverno Ross et al., 2018). “Transportation walking” measured whether a child frequently/always engaged in any versus no transportation-related walking (e.g., walking to school). Similarly, recreational walking was measured using one dichotomous dependent variable. “Recreational walking” measured whether a child was frequently/always engaged in any versus no recreational walking (i.e. walking the dog).

2.4 Analyses

2.4.1 Geographically Weighted Regression

Geographically weighted regression (GWR) is an exploratory technique adopted in relevant literature largely to deal with spatially varying variables. Previous research investigating the relationship between urban form and pedestrian behavior applied global regression models only. However, since the present study includes urban, suburban, and peripheral areas with differing urban form characteristics, it is plausible that the relationship between urban form and walking varied across the study area. Although some studies have discovered that the relationship between socio-economic status and walking is a stationary process (i.e., socio-economic attributes would be expected to be

associated with walking in all areas), structural features are likely local factors with significant geographical variations (Fotheringham et al., 2002).

Geographically weighted regression (GWR) technique is a model-building tool, which provides relatively more precise results if the relationship between variables shows spatial nonstationary characteristics (Fotheringham et al., 2002). Since GWR technique calculates the relationship between variables with a different coefficient for each geographical unit, it is possible to map where the relations are weak and strong, significant and insignificant. It is more explanatory than global regression, since it can explain via maps the relationship between two variables for each observation in geography with a different LOG ODD (odds ratio, *OR*) coefficient. Equation (1) shows the (nxn) dimensioned diagonal weighted matrix constituted by (1,2,3…….n)

$$W_i = \begin{bmatrix} w_{i1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & w_{in} \end{bmatrix} \qquad (1)$$

GWR forms weighted matrix for each i. These weights vary in accordance with the position of each i. Thereby, closer positions get more weights. The heterogeneous distribution of the relationship between two variables, which can be positive or negative and strong or weak in accordance with the location, can be reflected on space with the use of GWR technique.

In this study, a multiple Logistic GWR model is used to assess the relationship between urban form measures (land-use and street connectivity characteristics around homes—the independent variables) and the binary outcome variables (transportation and recreational walking—the dependent variables). To determine which model is appropriate, a comparison between logistic GWR and logistic regression has been performed. The model with lower AIC values was found to be a better fit (Fotheringham et al., 2002; Tu and Xia, 2008; Wang et al., 2005).

Geographically weighted regression software (GWR4.0) was used to identify the locations (points) where the odds of walking (for transportation/recreational) increase as there are changes within the independent variables. The results of the logistic GWR were mapped in ArcGIS, version 10.2, to allow visualization

of the spatial relationships (Figures 4-5). Even though there is a discontinuity within the region of study (between the districts served by three southern schools and the districts served by the remainder), the optimal bandwidth was selected based on multiple tests, which assured that the empty spaces were outside of and far from the study points. Hence, this gap in coverage is unlikely to have any impact on the modeling results.

3. Results

3.1 Descriptive Statistics

A total of 20 schools located in 5 different districts was included in the analysis. Descriptive statistics related to urban form characteristics of these districts, summarized based on 400-meter aerial buffers around homes of participants located in each district, are shown in Table 1.

Table 1. Urban form characteristics of selected areas in terms of their districts. (N=917).

	Ataşehir	**Kadıköy**	**Kartal**	**Ümraniye**	**Üsküdar**
Numbers of selected schools and home areas					
Number of selected schools	4	6	3	3	4
Number of home areas measured (400m buffers)	162	165	202	186	202
Characteristics of street network configuration					
Average Integration (r:3)	2.057	1.908	1.966	2.106	2.007
Average metric reach (400m)	4.290	3.164	4.199	4.437	3.915
Average 2-directional reach (20°, 2 direction changes)	0.521	0.783	0.439	0.617	0.361
Land-use characteristics (in thousands)					
Average total residential sq mt	84,341.4	77,317.0	83,079.9	85,863.5	114,492.3
Average total recreational sq mt	3.35	3.50	2.17	1.68	1.84
Average total commercial sq mt	241.41	238.31	236.58	240.80	92.01

This preliminary benchmarking demonstrates notable differences between areas[3]. The areas summarized in terms of their districts differ significantly in their average street density. Average metric reach, from high to low, is consistently in descending order from Ümraniye to Ataşehir, Kartal, Üsküdar, and Kadıköy for radii of 400 meters. However, Kadıköy has the highest two-directional reach, whereas Üsküdar and Kartal have similar lower averages. The magnitude of land-use densities follows a similar order as that of spatial values. Ataşehir and Ümraniye have the highest commercial square meters while Üsküdar, which is primarily a residential district, has the lowest commercial use density. In terms of residential building square meters, Üsküdar has the highest density while Ümraniye, Ataşehir, and Kartal are found to have similar densities for a 400-meter buffer range, with Kadıköy having the lowest density.

Respondents with missing data for children's activity types (*n*=344) were excluded from the analyses. Overall, a total of 917 parents completed the questionnaires related to their child's walking activity. Fifty-four percent of children were girls, and 46% of them were boys. 573 children (62%) walked frequently/always for transportation purposes, and 821 students (89%) walked for recreation purposes within their neighbourhood.

Table 2 summarizes the descriptive statistics for all the independent variables used in statistical analysis.

Table 2. Descriptive statistics for the independent variables used in statistical analysis. (N=917).

	minimum	maximum	average	median	std Dev.	SEM
Integration (r:3)	1.76	2.99	2.31	2.28	0.23	0.01
Metric reach	2.98	5.68	4.02	4.23	0.85	0.03
Directional reach	0.01	1.30	0.53	0.55	0.24	0.01
Residential use(sqmt)	21052.3	171165.7	89750.1	89029.6	29474.00	973.3
Commercial use(sqmt)	0.00	416.14	206.76	221.13	81.33	2.69
Recreational use(sqmt)	0.00	5.22	2.45	3.005	1.627	0.05
Mother education	1.00	6.00	3.26	3.00	0.97	0.03
Father education	1.00	6.00	3.49	3.00	1.01	0.03

[3] Overlaps across individual residences were double counted.

Household Income	1.00	5.00	1.91	2.00	1.26	0.04
Car ownership	0.00	5.00	1.50	1.00	0.68	0.02
Neighbourhood education	8.43	53	25.14	23.33	10.61	0.35
Distance to centres (mt)	113.1	5423.3	2379.1	2064.7	1326.4	43.8

Mother/father education: 1: illiterate, 2: literate, 3: primary school degree, 4: high school degree, 5: college degree, 6: postgraduate degree
Household income (USD): 1:1-230, 2:231-603, 3:604-1086, 4: 1087-1569, 5:>1570
Car ownership: continuous numbers
Neighbourhood education: % of inhabitants with a college and/or postgraduate degree within a neighbourhood
Distance to centres: linear distance measured from homes to major activity (commercial, retail, and business) centres

3.2 Comparison with the logistic regression model

The results of the multivariate global logistic regression models for transportation and recreational walking are shown in Tables 3a-d. A set of multivariate models were estimated using various urban form and SES variables together, controlling for distance to centres, whether or not the participant resides within 400m. of schools as well as two dummy-coded variables: “district” and “school”. Nineteen district variables were created using Ataşehir district as the reference category, since it has medium range of connectivity levels. Participants residing within this district were coded 1, and were coded 0 if not. TEB Elementary school within this district was used as the reference category for school dummy variable. Similarly, participants attending this school were coded 1, and were coded 0 if not. The global models demonstrated significant and positive associations only with recreational density levels and recreational walking (Tables 3b,d). Increased recreational use within 5-minutes of walking is associated with increased likelihood of walking for recreation purposes. No significant relationship was found with other urban form or SES variables.

Table 3a. Results of global logistic models for transportation and recreational walking (frequently/always), including residential land-use density and Directional Reach (20°, 2-direction changes), controlling for parental education, distance to centres, school district as well as school and district dummy variables. N=917.

Global (logistic)							
	Coefficient	SE	AIC_c		Coefficient	SE	AIC_c
Transportation walking				Recreational walking			
Residential use	0.00	0.00	1223.40	Residential use	0.00	0.00	622.20

Directional reach	0.10	0.09		Directional reach	0.027	0.58	
Parent education	-0.03	0.17		Parent education	0.04	0.03	

**p,0.01, *p<0.05
Analysis is adjusted for “school” and “district” variables.

Table 4b. Results of global logistic models for transportation and recreational walking (frequently/always), including recreational land-use density and Integration (r:3), controlling for neighbourhood education, distance to centres, school district as well as school and district dummy variables. N=917.

Global (logistic)							
	Coefficient	SE	AIC_c		Coefficient	SE	AIC_c
Transportation walking				Recreational walking			
Recreational use	-0.06	0.11	1223.62	Recreational use	0.02**	0.01	609.65
Integration (r:3)	-0.05	0.13		Integration (r:3)	-0.01	0.08	
Neighbourhood education	-0.00	0.00		Neighbourhood education	0.00	0.00	

**p,0.01, *p<0.05
Analysis is adjusted for “school” and “district” variables.

Table 5c. Results of global logistic models for transportation and recreational walking (frequently/always), including commercial land-use density and Integration (r:3), controlling for household income, distance to centres, school district as well as school and district dummy variables. N=917.

Global (logistic)							
	Coefficient	SE	AIC_c		Coefficient	SE	AIC_c
Transportation walking				Recreational walking			
Commercial use	0.00	0.00	1224.22	Commercial use	0.00	0.00	621.23
Integration (r:3)	-0.04	0.13		Integration (r:3)	-0.04	0.08	
Household Income	0.00	0.01		Household Income	0.01	0.01	

**p,0.01, *p<0.05
Analysis is adjusted for “school” and “district” variables.

Table 6d. Results of global logistic models for transportation and recreational walking (frequently/always), including recreational land-use density and Directional Reach (20º, 2-direction changes), controlling for parental education, distance to centres, school district as well as school and district dummy variables. N=917.

Global (logistic)							
	Coefficient	SE	AIC_c		Coefficient	SE	AIC_c
Transportation walking				Recreational walking			

Recreational use	-0.01	0.01	1222.42	Recreational use	0.18**	0.01	614.63
Directional reach	0.12	0.09		Directional reach	-0.01	0.06	
Parental education	-0.03	0.04		Parental education	0.04	0.03	

**p,0.01, *p<0.05
Analysis is adjusted for “school” and “district” variables.

The same sets of variables are modeled using multiple local logistic GWR analysis. However, due to limited space, two local logistic GWR models with different variables, controlling for distance to centres and whether or not the participant resided within 400m. of schools (a proxy for school-district), are reported here. Tables 4a-b show the result of these logistic GWR models for transportation walking and recreational walking. All the variables show nonstationary relationships with the outcome variable. Street connectivity coefficients ranged from -1.99 to 0.81 and from -1.35 to 3.43 for Directional Reach for transportation and recreational walking respectively and from -0.06 to 0.89 and from -2.24 to 1.14 for Integration (r:3) for walking for transportation and recreational purposes respectively. The difference between the minimum and maximum local coefficients indicates that urban form affects walking unequally across space. All urban form variables, except for residential use, exhibit both positive and negative effects depending on the specified locations. Those results explicitly account for spatial heterogeneity distributions of the relationships between street connectivity and walking behaviour. In addition, when the corrected AIC values are compared across models (Tables 3a-b versus Tables 4a-b), it becomes evident that the local logistic GWR model is a better fit for both urban form and SES variables. Hence, spatial heterogeneity is addressed by considering spatial variation.

Table 4a. Results of GWR models for transportation and recreational walking (frequently/always) including residential land-use density and Directional Reach (20°, 2-direction changes), controlling for parental education, distance to centres and school district. N=917.

Local (logistic GWR)									
	Coefficient			AIC_c		Coefficient			AIC_c
Transportation walking	Min.	Max.	Median		Recreational walking	Min.	Max.	Median	
Residential use	0.00	0.00	-0.00	1207.29	Residential use	0.00	0.00	0.00	618.90
Directional reach	-1.99	0.81	-0.30		Directional reach	-1.35	3.43	-0.51	
Parental education	0.00	0.00	-0.05		Parent education	-0.39	0.38	0.13	

Table 4b. Results GWR models for transportation and recreational walking (frequently/always) including recreational land-use density and Integration (r:3), controlling for neighbourhood education, distance to centres and school district. N=917.

Local (logistic GWR)									
	Coefficient			AIC_c		Coefficient			AIC_c
Transportation walking	Min.	Max.	Median		Recreational walking	Min.	Max.	Median	
Recreational use	-1.59	1.37	-0.15	1214.53	Recreational use	-0.29	0.49	0.15	603.87
Integration (r:3)	-0.06	0.89	0.00		Integration (r:3)	-2.24	1.14	-0.61	
Neighbourhood education	-0.02	0.01	0.38		Neighbourhood education	-0.02	0.09	0.16	

3.3 Interpreting the logistic GWR results

Figures 4-5 illustrate the parameter estimates (t-values) of selected urban form variables respectively estimating the variation in transportation and recreational walking. As expected, positive and negative clusters emerge across the map. T-values are significant in some areas ($p<0.05$ level, t values above 1.96 and lower than -1.96).

Figure 4a illustrates the effects of street network connectivity, measured by Directional Reach, and land-use, measured by residential use, on recreational walking, controlling for parental education, distance to centre, and whether or not the participant resided within 400m. of school. While residential land-use density proves to be insignificant, there is a marginal but significant relationship between directional accessibility and walking behaviour, though only in one section of the city. The map shows that increased directional accessibility is associated with increased odds of recreational walking only in a section of the peripheral district Ümraniye. In other words, children residing in this part of the city, where a strong differentiation between scales of connectivity structure is evident (supergrids of primary roads, with inserted organic local streets), are more likely to walk for recreation purposes than those living in areas where the street network layout has a more homogenous spatial structure (i.e. uniform grid-like or organic). This can be due to the fact that increased linear extension of few long streets, which form the primary connecting system of the

neighbourhoods, affect the willingness of children to walk for recreational purposes within their home-environments. On the other hand, directional accessibility is inversely associated with transportation walking (Figure 4b) in the peripheral Kartal district. Similarly, in this district, decreased residential density is associated with increased odds of transportation walking behaviour. This finding suggests that decreasing residential density, and in turn increasing commercial activities, within peripheral neighbourhoods might increase the odds of walking for transportation by allowing children to link their trips on foot. This finding is in conformity with recent research suggesting that pedestrian movement levels decrease with increased residential density (Kang, 2015; Ozbil et al., 2015).

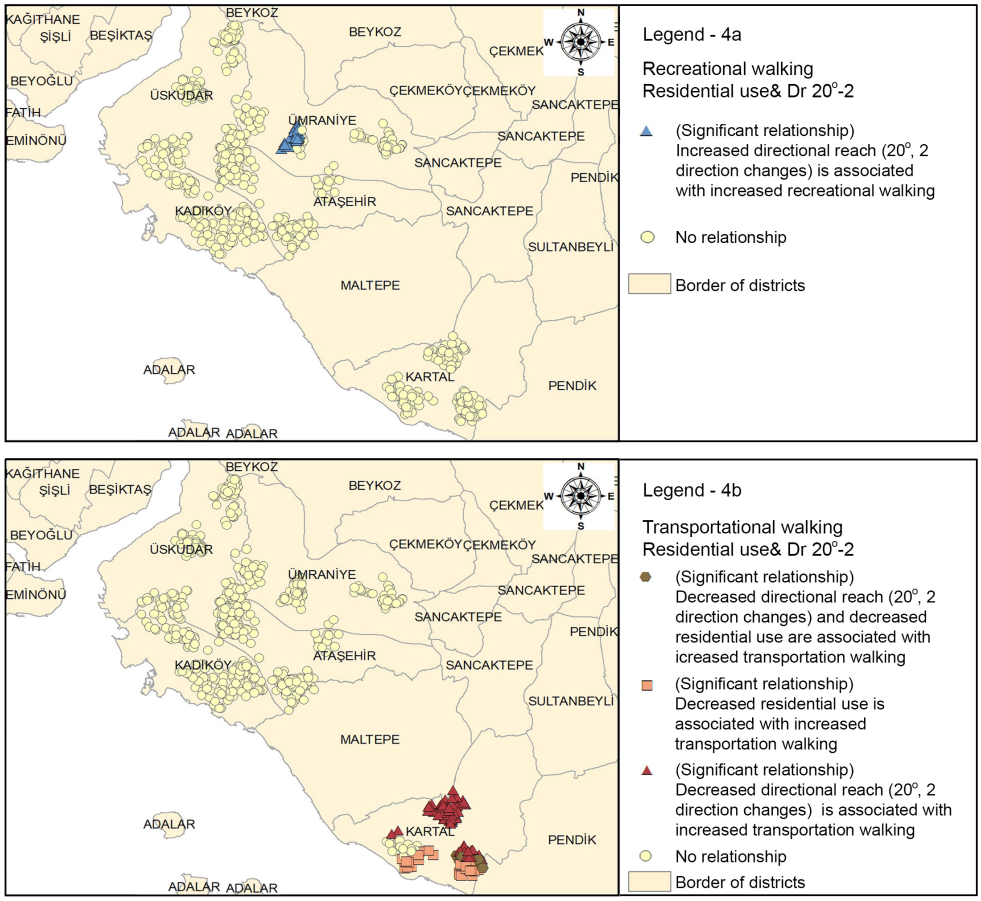


Figure 4. Results of logistic geographically weighted regression model of recreational walking (a) and transportation walking (b); demonstrating t-values for Directional Reach (20º, 2-direction changes) and for residential density, controlling for distance to centres, whether or not the participant resides within 400mt. of schools, and parental education.

Similarly, there is a marginal but significant relationship between urban form factors and recreational walking behaviour in the local logistic GWR model modeling the spatial variation in Integration (r:3) and recreational density (Figure 5a). No significant association was found between urban form variables and transportation walking. As seen in the map, increased recreational density in the peripheral district Ümraniye, which has the lowest recreational activity levels among the study areas, is associated with increased odds of recreational walking. This finding is critical since it demonstrates that particularly in districts that lack in recreational uses, having higher densities of recreational activities (i.e. parks, playgrounds, etc.) within a 5-minute walking distance of homes encourage children to walk more for recreation purposes. This result supports earlier research arguing that the presence of parks within walking distance of one`s home may promote recreational walking (Leslie et al., 2010; Sugiyama et al., 2010).

In terms of street network configuration, Integration (r:3) levels of street network are inversely associated with recreational walking only in a limited area. In this area, which is located at the edge of the city, increased Integration (r:3) levels are associated with lower odds of recreational walking. A more detailed investigation into the map shows that in this area commercial land-uses are distributed unevenly, with higher density of retail, office, and commercial buildings located along certain axes. Hence, the effect of street connectivity is overcome by the effect of land-uses. This phenomenon may suggest that the probability of walking for recreation purposes within home environments is dependent in particular on the interaction between street network configuration and land-use compositions at the local level (400m. radii). Hence, the spatial distribution of the relationship between street network connectivity and recreational walking demonstrates that the interaction between the two variables cannot be considered independently of land-use distributions within an area.

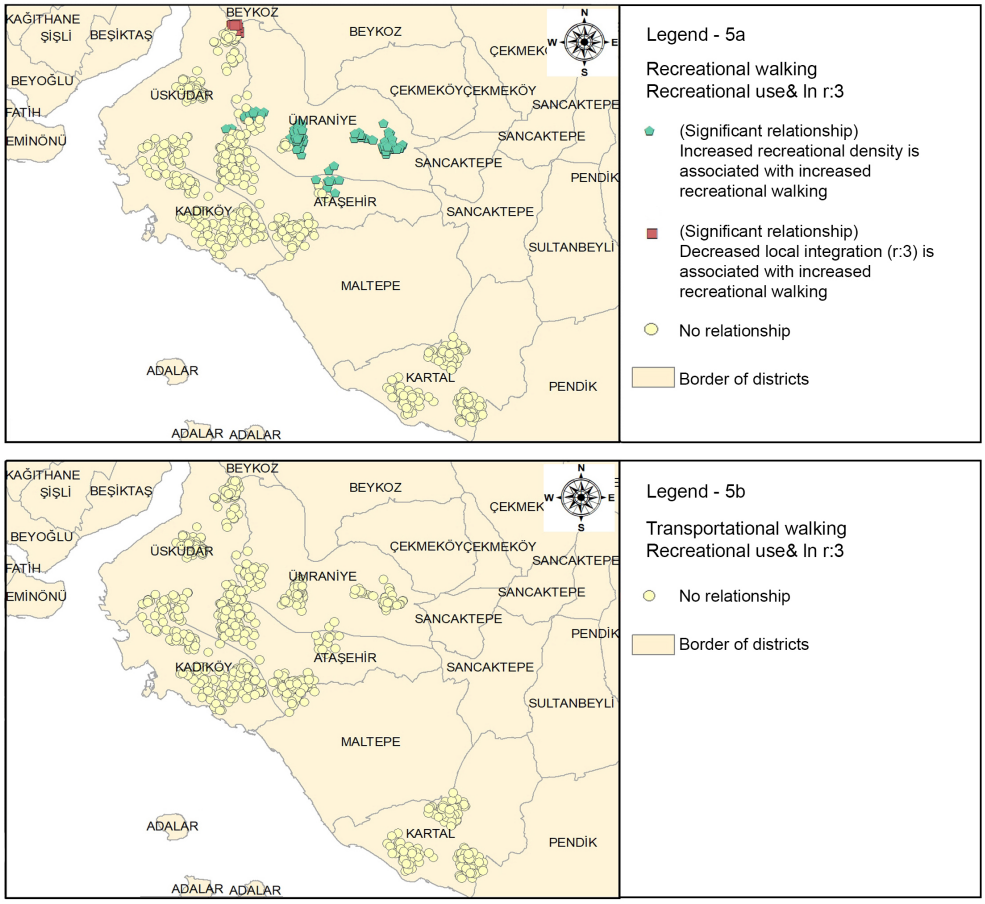


Figure 5. Results of logistic geographically weighted regression model of recreational walking (a) and transportation walking (b); demonstrating t-values for Integration (r:3) and for recreational density, controlling for distance to centres, whether or not the participant resides within 400m. of schools, and neighbourhood education.

4. Discussion

This study presents a data-driven framework for understanding the relationship between urban form and walking behaviour using multiple logistic GWR models. This study focused on children aged 12–16 years in Istanbul, Turkey, to determine the association of urban form, measured through land-use density and street network configuration, with transportation and recreational walking, taking into account parental socio-economic status (SES).

These results show a marginal but significant relationship between urban form factors—street network configuration and land-use density—and walking (for both transportation and recreational purposes) in some sections of the city. The

model results confirm that the effects of street network connectivity and land-use density vary with the spatial distribution of children. In the present study, the positive association of increased street network connectivity with recreational walking, controlling for parental education, distance to centres and whether or not the participant resides within 400m. of schools, is consistent at certain locations for only the configurational variable of Directional Reach. It is shown that increased directional accessibility is associated with increased odds of recreational walking in particular peripheral areas where a strong differentiation between scales of connectivity structure is evident (i.e. a supergrid of primary roads with inserted organic local streets). Hence, this indicates that reducing direction changes of primary connecting streets and increasing street network density of secondary streets attached to them within a 5-minute walking range of homes in such peripheral areas would significantly increase the odds of children's walking for recreational purposes, such as walking for leisure pursuits, within their neighbourhood.

However, findings also indicate that street network configuration does not work independently of land-use patterns. Children residing in such neighbourhoods with reduced residential land-uses (increased commercial activities in return) along primary roads with increased linear extension are more likely to walk for transportation purposes than are those living in neighbourhoods where there is increased density of residential land-use along a more homogenous street network. This finding conforms to patterns found in past studies indicating the relationship between street network layout, land-use, and walking (Lee and Moudon, 2006b; Ozbil and Peponis, 2012) and provides important evidence for planners and policy makers to use to effectively design neighbourhoods aimed to encourage walking behaviour, especially among children. The investigation of the parameter estimates of the local models also suggests that increased density of recreational land within home environments in peripheral areas lacking in recreational uses increased the odds of walking for recreation-related purposes when analysed at a 400-meter range. This supports the findings of various studies highlighting the significance of recreational activities within neighbourhoods in recreational walking behaviour (Li et al., 2005; Sugiyama et al., 2014).

5. Strengths and Limitations

The current study has addressed some of the analytical issues with previous walkability studies by using segment-based connectivity measures. These measures are sensitive to the shape and alignment of streets, not merely to their density, and can differentiate between closely located street segments within the same network. Previous studies on walkability have used average measures of connectivity, such as the number of urban blocks per area or average block size. Connectivity measures that describe the average properties of areas may be useful in supporting urban design guidelines and planning policies, but they fail to evaluate spatial structure of street networks, and hence cannot inform design decisions regarding the creation of new streets or the realignment of existing ones.

In addition, recent studies using space syntax measures of street network configuration have mostly analysed data at the global level (OLS or logistic regression). Whereas space syntax theory considers space as heterogeneous with differing street network configurations, standard OLS or logistic regression techniques applied by space syntax literature regards space as nonstationary. However, the standard regression techniques tend to omit certain variables, which tend to serve as significant factors underlying walking behaviour. For example, as seen in the comparisons between the logistic regressions and logistic GWR models in this study, the spatial variation in the effect of land-use on walking is interesting and may explain the insignificance of these variables in the logistic regression model. This research fills this gap by presenting an innovative framework that integrates logistic geographically weighted regression (GWR), which identifies area hotspots or vulnerable neighbourhoods, with spatial modeling, which evaluates the impact of street network configuration on walking behaviour in these neighbourhoods. A significant contribution of mapping out the results of logistic GWR models lies in showing that factors encouraging recreational and transportation walking might differ. For example, increased recreational density within home environments has a positive association with walking for recreational purposes, while no relationship is found between recreational land-use and transportation walking.

Moreover, this study uses small-scale measurements (i.e., parcel, street segment) that are far more realistic and refined than the generally used large geographic units (i.e., census tracts or traffic zones). Hence, problems related to measurement errors have been avoided.

Because there is no study reporting children's walking frequencies for transportation and recreational purposes specifically in Istanbul, this study is the first study, to the knowledge of the authors, to offer detailed data on children's walking behaviour in the city. This study also contributes to the literature in that it is one of the first Turkish studies to empirically establish a relation between urban form factors and children's walking behaviour. It also adds to the limited literature on the neighbourhood street network configuration in Turkish cities; the limited literature on the environment-walkability link is dominated by the North American context. Although results are tempered by several limitations, the study has significant implications for planners, urban designers, and policy makers involved in the development of children's environments.

A significant limitation of the study is that because the outcome variables are dependent on parents' answers to the questionnaires, there might have been some misrepresentation of children's walking behaviour, but the study area includes more than 900 data points. The sample size becomes even more important when applying GWR models given that false positive rates for GWR coefficients may be achieved in studies with small sample sizes (<160 data points) (Paez et al., 2011). This study used a cross-sectional data set; hence, causal relationships between urban form, SES, and walking cannot be inferred. Longitudinal studies have reported few associations between neighbourhoods and physical activity for adolescents (Evenson et al., 2010; Neumark-Sztainer et al., 2003). Thus, this study needs be supplemented with longitudinal data to control for self-selection (whether people with preferences for walking select to locate at more walkable environments). Another limitation of the study is the use of partial neighbourhood-level socio-economic variables (e.g., neighbourhood-scale income) due to the limited availability of such data.

Further research needs to complement the models presented in this study with the use of complete neighbourhood socio-economic variables. Moreover, using `network` buffers instead of `aerial` buffers could provide to a more accurate representation of walkability.

6. Conclusion

Walking behaviour among children was associated with urban form characteristics only in certain peripheral parts of the city. Increased odds of walking for recreation purposes were associated with increased street network connectivity in certain neighbourhoods with particular characteristics (increased differentiation of connectivity structure). This highlights the significance of planning a dominant foreground structure through the creation of supergrids with traversing local main streets and internal street infills, as argued by Feng and Peponis (2018) and Scoppa et al. (2019). On the other hand, no significant association was found between street network connectivity and walking behaviour in central parts of the city. This might suggest that in central areas, which is dominated by increased connectivity and well-distributed commercial activities within neighbourhoods, walking can be supported by other factors, such as the increased urban design qualities of the street-environment. This finding holds potential benefits for planners and policy makers because it demonstrates that the one-size-fits-all approach may not effectively encourage walking, since, as the maps presented in this study demonstrate, urban areas tend to have varying qualities that need to be handled exclusively. Targeted rather than blanket interventions regarding the design of neighbourhoods around schools and homes may be beneficial in supporting walking behaviour of children, given that the present study has shown that the relationship between connectivity and walking varied over space; in peripheral areas with well distributed commercial land-use along the linear primary street network structure, the odds of walking increased, whereas in other areas, street connectivity was not associated with the odds of walking. Thus, interventions and policies aimed to create a differentiated street network structure (a primary skeleton system of few long primary streets to which many shorter local streets can be attached) within 5 minutes of walking around homes

in peripheral areas may be a key to promoting walking among children. This finding is important because walking is interrelated with a variety of benefits, including but not limited to public health (decreasing obesity rates) and sustainable cities (increasing non-motorized travel) (Ellis et al., 2015). Although the findings of this study must be regarded with caution since the associations were limited to a small part of the city, the proposed framework can help guide designers, planners, and policy makers in developing local interventions intended to create walkable environments.

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