Home and School Environmental Correlates of Childhood BMI

Abstract

Background: Active commuting to school can be a substantial opportunity to provide the necessary daily physical activity for children and to counteract childhood obesity. This paper examines the associations of urban form, in general, and street network design, in particular, with body mass index (BMI) in children aged between 12 and 16, controlling for socio-economic features (gender, educational attainment, income, and auto ownership) and daily physical activity (access mode to/from school and walking behaviour).

Methods: Data were drawn from questionnaires conducted in 20 elementary schools located in the Anatolian part of İstanbul, Turkey. Randomly selected 6th, 7th, and 8th grade students (N=1784) completed questionnaires regarding their commuting modes to/from school while their parents (N=1118) completed questionnaires about their socio-economic characteristics and their children`s daily physical activity. Each student's BMI was calculated by measured height and weight data. Home- and school-environments (800-and 1600-meter buffers around the respondent and school) were evaluated through GIS-based land-use data and segment-based street connectivity measures. Selected street segments within school-environments were also audited with regard to pedestrian environment characteristics.

Results: Findings indicate that children who actively commuted to/from school had lower BMIs than non-active commuters. More importantly, it is shown that increased street network connectivity measured at the segment-level is significantly associated with reduced BMI in school children. In fact, connectivity measures appear to be the strongest correlates of BMI.

Conclusions: This study provides important evidence for planners, urban designers, and policy makers on the significance of built environment, in general, and street network configuration, in particular, within home- and school-environments. One rule of thumb would be to design a well-connected street network with relatively denser connections and reduced direction changes within the neighbourhood – not only within a couple of blocks of homes and schools but also within their larger fabric (800-1600mt buffers).

Keywords: childhood obesity; urban form; socio-economic characteristics; street connectivity; İstanbul

1. Introduction

Childhood obesity has become an important health problem throughout the world as a result of increasing prevalence over the last two decades. According to research of NCD Risk Factor Collaboration (2017) the number of children and adolescents with obesity aged between 5 and 19 has increased more than 10 times in last four decades and has risen from 11 million to 124 million according to 2016 estimations. This rising trend manifests itself also in the Turkish case. According to a recent report, 8% of children aged between 6-18 is on the limit of obesity (Şık 2017).

The increase in the prevalence of obesity among children has drawn attention of various disciplines into the obesity epidemic. Several studies in the fields of health and sociology have demonstrated the impacts of genetic and socio-economic (gender, education opportunities, income level, car ownership, etc.) factors on the prevalence of obesity (Frank *et al.* 2003; Sallis and Glanz 2006; Bodea *et al.* 2008; Farajian *et al.* 2013). These studies showed that increased family income levels and decreased daily calorie amounts reduce the prevalence of obesity (Süzek *et al.* 2005; Loureiro and Nayga 2006; Frederick *et al.* 2014). Although most studies could not find any substantial association between family education levels and formation of obesity (Himes and Reynolds 2005), Kant and Graubard (2013) discovered that income and education levels of parents may increase energy intake and amount of foods which can be related to overweight and/or obesity.

On the other hand, researchers of urban design and planning have highlighted the significance of physical activity in the struggle against obesity. Walking as a moderate daily activity may significantly contribute to children's daily physical activity levels, thus helping prevent obesity in children (Bahrainy and Khosravi 2013, Brown *et al.* 2013). In this sense, active commuting to school can be a substantial opportunity to provide the necessary daily physical activity for children and to counteract childhood obesity. Studies have shown that children who walk to/from school are more physically active than those who use inactive modes of transportation (Roth *et al.* 2012). However, they could not find any association between walking and weight status (Cooper *et al.* 2003), which is one of the purposes of this research.

There are various factors that affect daily physical activity and active commuting to school. Alongside the individual and socio-economic factors, experts in urban design and urban planning emphasize the impacts of built environment on physical activity (Durand *et al.* 2011; McCormack and Shiell 2011) and highlight the importance of considering built environment factors to understand and reduce obesity (Sallis and Glanz 2006; Miranda *et al.* 2012; Marshall *et al.* 2014). A growing body of research has demonstrated that urban form characteristics (such as land-use and street layout) of children's neighbourhoods can have both positive and negative impacts on their physical activity levels (Larsen *et al.* 2009; Ding *et al.* 2011). For instance, recent research shows that children living in pedestrian-friendly environments have higher proportions of daily walking (Carver *et al.* 2019) and lower rates of body mass index (BMI) (Carroll-Scott *et al.* 2013). Although there is a plethora of research on the associations of urban form, physical activity and obesity, particularly in the study of obesogenic neighbourhoods, relatively little is known about the relationship between street network configuration and children's health. A key underlying reason is that in most small-scale research designs that accompany studies on walking behaviour the range of environmental variables considered is almost entirely concerned with local qualities of the environment (i.e. sidewalk quality). However, walking occurs not only to the fine grain of environment, but also to its larger scale structure. Hence, walking behaviour prevalent in an area cannot be described by analysing the immediate neighbourhood isolated from its global surroundings. Accordingly, environmental factors considered need to be associated with the character of an area- a neighbourhood, a district or a city. On the other hand, macro-scale studies of urban and traffic planning research apply relatively large units of analysis (e.g. Traffic Analysis Zones), failing to consider the effects of micro-scale design measures (street-level) on walking. Even more crucially, these standard objective street connectivity measures (e.g. intersection density in an area) fall short in describing the spatial and structural pattern of street networks that define an urban area.

The significance of the spatial structure of street networks in explaining walking behaviour has been apparent in recent studies based on space syntax theory (Baran *et al.* 2008, Lamiquiz and Lopez-Dominguez 2015, Koohsari *et al.* 2016). Spatial structure may be defined as the collection of streets and street segments through certain alignments and hierarchies. Space syntax still represents a rare attempt to develop empirically tested models to investigate the relationship between the built environment, social interactions, and movement (Hillier, 1996, Hillier and Hanson, 1984, Peponis and Wineman, 2002) and thus is of particular relevance to this research. Space syntax is built on the architectural theory that space can explain human movement potentials and thus is correlated with the distribution of flows. Evidence from earlier studies applying space syntax methodology suggests that streets that are accessible from their surroundings with fewer direction changes tend to attract higher densities of pedestrian flows (Hillier *et al.* 1993, Peponis *et al.* 1997). Recent studies have shown that the structure of an urban street network, as defined by the connectivity hierarchy measured by direction changes, plays an important role in pedestrian travel (Hillier and Iida 2005; Ozbil and Peponis 2011; Ozbil *et al.* 2016).

This study focuses on the structural qualities of street network design in objectively describing the spatial pattern of the urban fabric at both a local and global level. As such, this paper applies small-scale urban form measures (segment-level[1] street connectivity and parcel-level land-use densities) to identify the extent to which street network design is associated with BMI in school children, controlling for socio-economic features (gender, educational attainment, income, and auto ownership) and daily physical activity (access mode to/from school and walking behaviour).

2. Methods

2.1 Sampling

Data for this cross-sectional study were drawn from questionnaires conducted in 20 elementary schools located within the Anatolian part of İstanbul, Turkey. The sampled schools were selected from neighbourhoods of varying household education levels and street network configuration across the city (Figure 1) to represent the full diversity of social and environmental factors that children experience around their homes and schools. A matrix was generated based on average values (e.g. high connectivity and high education) and schools falling in each category were selected as case studies. Integration, as used to determine the connectivity levels of street segments within the network, measures how close each segment is to all the others within a radius. In other words, the higher is the integration, the more central and nearer is the segment to all the segments within the network. Previous research suggests that integration exhibits a strong relation with pedestrian movement (Hillier and Iida 2005) and vehicular movement (Chiaradia 2007). In Figure 1 red and blue indicate higher and lower

[1] The segment is the section of axial line or street lying between two intersections.

Integration values respectively. Case study schools were selected from both integrated and segregated spaces within the Anatolian part of the city.

Students in grades 6, 7, and 8 (ages 12-16) at these schools (~100 students per school) were selected randomly based on the availability of their class schedules to take part in the study. They were asked to complete questionnaires that asked for their full address, gender, and various behavioural habits related to daily physical activity. Non-active commuters to/from school also reported the primary reason underlying the decision not to walk to/from school. Their parents were also invited to answer questions regarding their income, car ownership, education, and their children's physical activity levels. Those preventing their children from actively commuting to/from school also reported the reasons underlying their decisions. Student surveys were conducted face-to-face, whereas questionnaires were sent to parents via children. The underlying reason for studying the Anatolian part is due to the different urban patterns dominating each continent. The European part is mostly dominated by high-rise mass housing, service and commercial land-uses, whereas the Anatolian part reflects mostly a residential character with mixed land-uses prevailing the central parts. Although the selected areas represent a small cross-section of the entire city, the sum of their population equals to one-sixth of İstanbul's total population.

Ethics approval was granted by Human Ethics Commission, Özyeğin University (Ethics ID 2013/03) and relevant permissions were granted by the İstanbul Directorate of National Education (ID 59090411/605/2329961).

INSERT FIGURE 1 HERE

Figure 1. Location of surveyed schools, maps are coloured based on (a) global Integration values of the street network, and (b) the district-based average education

levels. Global Integration measures how easy it is to reach all segments within the system from each segment.

2.2 BMI

Height and weight of students who participated in the study were measured once during the questionnaires using an electronic scale (±50 gram precision) with a stadiometer. Body Mass Index (BMI) of participants was estimated by dividing weight in kilograms by height in meters squared. Age- and gender-specific BMI z-scores were calculated based on the World Health Organization growth curves for children aged between 5 and 19 (World Health Organization 2007). Participants were categorized as underweight, normal, overweight and obese using BMI z-scores. A total of 1784 out of 1973 students provided complete information on age, weight and height.

2.3 Daily physical activity

Survey questions regarding children's daily physical activity were based on NEWS (Neighbourhood Environment Walkability Scale) (Cerin *et al.* 2006). Data on the frequency of walking (days per week) between home and school, average daily walking minutes spent during a typical week, and the frequency of walking for any purpose (recreational and/or transportation) were collected through student and parent questionnaires.

2.4 GIS analysis of home and school urban form

ArcGIS 10.2.2 (Geographic Information Systems) (ESRI, 2014, Redlands, CA) was used to geocode the street addresses of participants on street network data based on Streetmap 2014 obtained from the İstanbul Metropolitan Municipality. The literature has shown 1 mile (1.6km) as the walking threshold between origins and destinations

(Davison *et al.* 2008) while 0.5 mile (800mt) is considered to offer more possibilities of active commuting (Riazi and Faulkner 2018). Hence, home- and school-environments (800 and 1600 meter circular buffers around the home and the school) were evaluated through GIS-based measures. Parcel-level land-use densities (residential, retail and recreational) were summarized for each buffer using 2014 GIS-based land-use data provided by the municipality. Figure 2 displays 800- and 1600-meter circular buffers of two schools from separate districts with different land-use densities. The urban school (top right) is located in a central city district, which has relatively smaller block sizes (average block size is 90x90mt) and a densely built up urban grid. The street network is relatively more continuous, and the urban form includes mixed-use activities (residential, retail, and other non-residential uses are distributed relatively homogenously). On the other hand, the in-town suburban school (bottom left) is located in a peripheral district near the edge of the centre. The area has relatively larger block sizes (average block size is 150x200mt) with many cul-de-sacs (relatively a more discontinuous street network). Even though the edge of the periphery includes some densely built-up areas, the immediate surroundings of the school (800-mt buffer) is mostly residential with retail activities dispersed unevenly within the neighbourhood.

INSERT FIGURE 2 HERE

Figure 2. 800 and 1600 meter circular buffers of two schools with different land-use densities.

Street network configuration within home- and school-environments was quantified using three different descriptors of spatial structure of street networks. *Connectivity* measures how many spaces (streets) intersect each segment. *Angular Segment Integration,* which measures the closeness centrality C_c of a graph as the reciprocal function of the sum of the shortest path between every origin and every destination, identifies how accessible each space is from all the others within the radius using the least angle measure of distance. Closeness centrality, C_c, is defined as:

$$C_c\,(P_i) = \left(\sum\nolimits_k d_{ik}\right)^{-1}$$

where *i* is the origin and *k* is the destination (Law *et al.* 2012). *Angular Segment Choice,* which measures the betweenness centrality of B_c of a graph, identifies the extent to which a node is located in between the paths connecting all pairs of origins and destinations (Hillier and Iida 2005). The angular betweenness value for a segment x in a graph of n segments can be defined as follows:

$$B_\theta(x) = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} \sigma\,(\mathrm{i}, x, \mathrm{j})}{(n-1)(n-2)}$$

such that $i \neq x \neq j$, where $\sigma(i, x, j) = 1$ if the shortest path from i to j passes through x and 0 otherwise (Turner 2007).

The latter two measures represent the *to* and *through* movement potential of the street segment (Hillier *et al.* 2012). In space syntax, Integration and Choice are computed at different ranges. Sometimes the whole system represented is taken into account in the calculation. At other times, analysis is constrained by specifying how many lines away from each line are taken into account in the calculation. Thus, for example, Integration radius 3 (r:3) means that closeness centrality is computed by considering each line as a root and allowing up to two additional lines to be taken into account in all possible directions. When small radii such as 3 or 5 are used in order to constrain the analysis, the results are taken to describe the “local structure” of areas. When the radius is not constrained, or when it is very large, the results are taken to describe the “global structure” of an area. Choice (B_c) and Integration (C_c) (r:n and 3) for 800 and 1600 meter radii were calculated separately. These measures were calculated using Depthmap software (Turner and Friedrich, 2010-11). Figure 3 illustrates global Integration (C_c), global Choice (B_c), and Connectivity respectively.

INSERT FIGURE 3 HERE

Figure 3. Representing a home-environment (1600 mt-radius) with different configurational measures.

2.5 Pedestrian Environment around Schools

Due to resource limitations, only 40 street segments within each school-environment (1600mt buffers) were audited through detailed field surveys to document the street-level pedestrian environment. The selection of audited segments were based on: (1) not a dead-end street, (2) representative of a wide range of Integration (r:n) values, and (3) having similar lengths. The pedestrian quality attributes to document were selected from local qualities of street environment that are shown to affect pedestrian movement behaviour via their impacts on people`s perception on safety and aesthetics (Pikora *et al.* 2003; Rodríguez *et al.* 2009; Asadi-Shekari *et al.* 2019). These include average sidewalk width as well as the presence of pedestrian crossings and street trees. Where available, sidewalk width on both sides of the segment was measured and the average width is included in the analysis. Similarly, the presence of crosswalks and trees for both sidewalks is considered (i.e. coded “yes” if there were trees on either side of the audited segment). The percentage of segments with crosswalks and street trees was then calculated.

2.6 Statistical analyses

Attribute tables containing the urban form variables by home and school for each participant were linked to questionnaire data on each student and parent within ArcMap

10.2.2 and exported for statistical analyses. Multivariate regression analyses were conducted in JMP (JMP®, Version 12.2.0 SAS Institute Inc., Cary, NC, 1989-2019) to examine the associations between urban form characteristics, socio-economic features, street-network configuration and physical activity in explaining individual BMI scores.

3. Results

Table 1 provides descriptive statistics for the demographic characteristics of the study participants. Nearly equal number of boys and girls participated in this study. ⅔ (61%) of participants were categorized as having a normal BMI, 22.4% were overweight, 12.6% were obese and 4.1% were considered underweight. Boys were much more likely to be obese than girls.

Table 1. Demographic Characteristics of Study Participants.

	All		**Underweight**		**Normal**		**Overweight**		**Obese**	
	n	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
All	1784	100.0	73	4.1	1087	60.9	400	22.4	224	12.6
Sex										
Boys	896	50.2	48	5.4	483	53.9	217	24.2	148	16.5
Girls	888	49.8	26	2.9	601	67.7	183	20.6	78	8.78
Age (years)										
12	345	19.3	5	1.45	208	60.2	77	22.3	54	15.7
13	601	33.7	41	6.8	349	58.1	134	22.3	74	12.3
14	590	33.1	20	3.4	360	61.0	138	23.4	70	11.9
15	183	10.3	5	2.7	120	65.6	32	17.5	17	9.3
16	11	0.6	1	9.1	7	63.6	3	27.3	0	0.0

The primary aim of this study was to identify the extent to which spatial configuration of street network was related in estimating BMI, controlling for socio-economic factors –gender, household income, car ownership, parental education- and physical activity –frequency of walking within home-environment and of walking as commuting mode between home and school. In order to compare the effect sizes of space syntax measures and standard connectivity measures, the measure of total number of street intersections was calculated as the number of intersections of three or more street segment endpoints within each home buffer (1600mt). The intersection density measure had a coefficient of determination of 0.39 ($p< 0.001$) while connectivity, C_c (r:n) and B_c (r:n) had coefficients of determination of 0.57, 0.71 and 0.41 (all $p<0.001$) respectively in relation to BMI. Since angular segment measures prove to be stronger correlates of BMIs than standard connectivity measure of intersection density, street network centrality measures are used in the multivariate regression models.

For home-environment, the model included network distance between home addresses and related schools as well as walking frequency around home (rarely versus frequently); while for school-environment, the model included the variables related to pedestrian environment around schools, the frequency of walking from home to school (rarely versus frequently) as walking behaviour variables. Tables 2 and 3 display the results of the multivariate regression analyses of the associations of the home and school urban form with children's BMI scores. For home-environment, the best fitting model was obtained for 1600 meter buffer, while for school-environment analysis the best results were obtained for 800 meters. Similarly, global (r:n) connectivity measures provided the best results for both types of analyses. Hence, these results are provided.

The results from multivariate regression analyses show that household income and car ownership are positively and significantly associated with children's BMIs. In other words, increase in average monthly household income and number of cars result in higher BMIs. However, the indicators for land-use variables in the home- and school-environment had no significant effect on the outcome variable. For street network configuration, both average connectivity and closeness centrality (C_c) are inversely and statistically significant. In fact, the standardized coefficients of both variables indicate that street network connectivity is the strongest predictor of the variation in children's BMI scores. Both for home- and school-environment models, walking frequency is inversely and significantly associated with the outcome variable. Higher walking frequency for any purpose around home (1600mt) results in reduced BMIs. Similarly, higher frequency of walking to school yields to reduced BMIs. Network distance between home and school addresses is also significantly and positively associated with BMI (Table 2). This finding, which suggests increased BMIs in children residing within relatively longer distances of their schools, is in conformity with previous findings indicating that active commuting to/from school, and in turn BMI, depends on the distance of walking (Sturm 2005; Wood *et al.* 2016). Results suggest that the variety within the pedestrian environment of schools also matter. Increased sidewalk width and street trees within walking environment are found to be significantly associated with decreased BMI, indicating that children choose to walk to/from school in walkable neighbourhoods supported with urban design attributes.

Table 2. Results of Multivariate Regression Analysis examining the relationship between home urban form, walking behaviour and children's BMI scores.

	students' BMI scores			
		β	t	stdβ
socio-economic				
	gender [female]	-1.18	-0.47	-0.02
	parental education[a] [≤college]	-1.68	-0.64	-0.03
	income	**2.19**	**2.59***	**0.10***
	car ownership	**4.45***	**2.19***	**0.09***
land-use (1600m)				
	residential	-0.00	-0.84	-0.03
	retail	0.01	1.69	0.07
	recreational	0.01	1.59	0.06
street network (1600m)				
	avg. connectivity	**-8.49****	**-5.04****	**-0.20****
	Closeness Centrality	**-0.06****	**-5.38****	**-0.24****
	Betweenness Centrality	0.17	1.86	0.08
network distance between	home and school	**7.79***	**2.33***	**0.10***
walking behaviour				
	walking frequency[b] (rarely)	**1.51***	**2.00***	**0.08****

bold **p<0.001; bold * p<0.05
[a] Either and/or both parents having a college or lower degree
[b] walking frequency around home (frequently versus rarely –the referent)

Table 3. Results of Multivariate Regression Analysis examining the relationship between school urban form, walking behaviour and children's BMI scores.

		students' BMI scores		
		β	t	stdβ
socio-economic				
	gender [male]	5.97	1.87	0.07
	parental education[a] [≤college]	-.00	-0.04	-0.02
	income	**3.21***	**2.99***	**0.12***
	car ownership	**0.00****	**3.54****	**0.15****
land-use (800m)				
	residential	0.00	0.91	0.05
	retail	0.00	1.80	0.10
	recreational	0.00	1.50	0.08
street network (800m)				
	avg. connectivity	**-0.00***	**-3.10***	**-.0.26***
	Closeness Centrality	**-1.35***	**-2.83***	**-0.18***
	Betweenness Centrality	0.03	0.16	0.01
walking behaviour				
	walking frequency[c] (rarely)	**0.00***	**2.58***	**0.10***
pedestrian environment				
	avg. sidewalk width	**-2.08***	**-2.75***	**-0.22***
	%segments with street trees	**-0.00***	**-2.38***	**-0.20***
	%segments with crossings	0.00	0.87	0.06

bold **p<0.001; bold * p<0.05

[a] Either and/or both parents having a college or lower degree

[c] Frequency of walking from home to school (rarely versus frequently –the referent)

Bivariate correlations are also conducted between street network connectivity measures and children`s physical activity levels, as measured through the children`s surveys, to understand the significance of connectivity for walking apart from BMI. The average connectivity and Closeness Centrality within 1600 meter buffers of homes had coefficients of determination of 0.57 and 0.68 (both p< 0.001) respectively in relation to the number of days per a typical week that the child walked more than 30 minutes. Similarly, connectivity and Closeness Centrality measures had coefficients of determination of 0.62 and 0.61 (both p<0.001) in relation to the total minutes the child walked per a typical day. Although these are just simple analyses and the outcome variables related to physical activity levels of children are limited, these results highlight the significance of street connectivity in terms of children`s walking behaviour as well as their BMIs.

The student surveys indicate that 64% of non-active commuters to/from schools would like to walk to/from school (Fig. 4a). Figure 4b shows the distribution of perceived barriers reported by students not willing to walk to/from school. The primary barrier is the long distance to school (56%), which is consistent with the statistical analyses. Other barriers to walking appear to be deserted roads (17%), heavy traffic (13%), neglected roads (5%), steep slope (5%) and lack of sidewalks (4%). These numbers identify street safety (physical and social) to be an important incentive to walk to/from school. Yet, both statistical analysis and interview results highlight distance to school as the main barrier to active commuting to/from school.

INSERT FIGURE 4 HERE

Figure 4. Student interview results: (a) percentage of non-active commuters willing or not willing to walk to/from school, and (b) perceived barriers to walking.

The parental perceived barriers to active commuting to/from school are coherent with those of children (Figure 5). ⅓ of parents prevent their children from actively commuting to/from school due to long distance to school and deserted roads. ⅕ of parents restrict their children`s active commuting due to unsafe roads (in terms of heavy traffic), while extreme weather conditions and lack of other children walking are the other reasons underlying parental decisions.

INSERT FIGURE 5 HERE

Figure 5. Parents` interview results regarding their perceived barriers preventing their children from walking to/from school.

4. Discussion

This study focused on children aged 12-16 years in İstanbul, Turkey to determine the association of urban form, measured through land-use density and street network configuration, with childhood obesity, controlling for socio-economic characteristics and daily physical activity. Among 1784 students, ⅔ (61%) of participants were categorized as having a normal BMI, 22.4% were overweight, 12.6% were obese and 4.1% were considered underweight. These findings are very similar to reported rates of overweight (20%) and obese (8.4%) among children aged 6-18 across Turkey (Oztora 2005).

Identifying the environmental determinants of children`s walking behaviour can help improve childhood health by contributing to the development of effective interventions aimed to increase active living. This study sheds some light on the extent to which the built environment is associated with childhood BMI in İstanbul. Multivariate regression analyses indicate that characteristics of street network around children's homes and schools have a modest but significant effect on their BMIs. In both models developed street connectivity was significantly related to BMI scores. In fact, standardized coefficients indicate that street network design has as strong associations with BMIs as socio-economic characteristics have. In addition, bivariate correlations between connectivity measures and children`s walking behaviour within their home-environments also highlight the significance of street network as an important correlate of walking. This indicates that urban policies aimed to create relatively higher connected street networks within school neighbourhoods might have as much, if not more, significant impact on fighting childhood obesity than would policies targeted towards bridging the gap between socio-economic inequalities. However; the most important contribution of this study is the finding that the spatial configuration of street network, measured through direction changes, is related to childhood BMI. Specifically, the models point to the fact that the spatial structure of street networks, specifically the alignment of streets and the directional distance hierarchy engendered by the street network, is a significant determinant of the variation in BMI scores, controlling for land-use and socio-economic factors. It can be argued that directional accessibility, measured through global Integration (C_c), affects childhood BMI indirectly through its effects on walkability. In other words, increasing the density of available streets and reducing direction changes within 800 meter of schools and 1600 meter of homes would encourage walking among children, and, in return, reduce the risk of increased childhood BMI.

Furthermore, this study demonstrated that the scale at which urban form has an impact on children's travel behaviour to/from school is of the order of 1600-meter radius, rather than a few blocks around the home. This is in contrast with the findings of previous studies and the conventional wisdom among planners which suggests 400 to 800 meters as walking distance threshold (Untermann 1984). Hence; direct and dense connections between activities (i.e. between residential and retail uses) and a connected street network with more direct connections between origin-destination nodes distributed evenly within 1600 meter of the school may influence children's travel behaviour and support walking as a mode of transport between home and school.

In addition, this study also revealed that income and car ownership are positively and significantly related to childhood BMI. The multivariate regressions between BMIs and the related variables demonstrated the effect and significance of each factor. This is consistent with earlier findings arguing that parental characteristics seem to be strong predictors of obesity rates in children (Brown *et al.* 2013). Although the positive relationship found between income and BMI is contrary to some earlier findings (Wang and Beydoun 2007, Huang *et al.* 2015), this finding may point to the interaction between income and various socio-economic attributes. Children of low-income families, who may not have cars to commute to school or cannot afford to use school shuttles, would be inclined to walk regularly to/from school. This, in return, would reflect as lower BMIs. Another explanation might be that in Turkey mid- and high-income groups have higher opportunity to eat out of home, including fast food (Akbay and Boz 2005). This finding is also in conformity with a recent study, which shows that in contrast to many developed countries, higher socio-economic levels are associated with childhood obesity in the Turkish case (Discigil *et al.* 2009). In terms of planning and urban design policy, laying out continuous and dense street networks around schools becomes even more important within low income neighbourhoods since children of lower income families, who lack access to cars and school shuttles, would be more inclined to walk to/from school.

The present study also confirmed patterns found in past studies that have shown the relation between daily physical activity and childhood obesity (Bahrainy and Khosravi 2013, Brown *et al.* 2013) as well as between distance to school and BMI (Rahman *et al.* 2011). The results of multivariate regressions demonstrated that increased daily walking frequency within the neighbourhood and as commuting mode to/from school had significant relationships with BMI. Similarly, increased distance to school was highlighted as a barrier to walking in both children's and parents' surveys and was found to be associated with increased BMIs in the statistical analyses. Results of multivariate models pointing to the relation between the variety within the pedestrian environment of schools and BMI also support earlier findings (Forsyth *et al.* 2008; Adkins *et al.* 2012). Increased sidewalk width and street trees along road segments support increased active commuting to/from school among children and, in turn, help reduce childhood BMI.

4.1. Strengths and limitations

One of the biggest contributions of this study is that it applies segment-based street connectivity measures that can measure the structural qualities of street network layout. The standard connectivity measures applied in the literature (e.g. total number of intersections per area) can measure the average connectivity of an area, but they fail to assess the spatial structure –the connectivity hierarchy measured by direction changes– that define an environment. The connectivity measures applied in this study highlight the significance of the spatial and structural pattern of street networks in explaining childhood obesity. The global connectivity measure (Closeness Centrality, r:n) is found to be a strong correlate of BMI; whereas no association is found between the outcome variable and local Closeness Centrality measure (r:3). These results point to the significance of the larger urban context in explaining childhood BMI through its effects on active commuting to/from schools. From the planning perspective, streets should be carefully laid out in a hierarchical manner (more integrated streets within their surrounding street system passing through the neighbourhoods, connecting the schools with the larger context). This planning strategy should be implemented not only in the immediate neighbourhoods of schools but also in the larger surroundings to promote long distance connections. In addition, this study offers reliable information on the actual addresses (point data) of the children. Since the majority of studies use larger units of address coding (e.g. census tracts), failure to measure the urban form around actual residences of participants poses a real challenge in clearly understanding the environmental correlates of walking behaviour.

This study also contributes to the literature since it is one of the first Turkish studies to empirically establish a relation between urban form factors and children's BMI. It also adds to the limited literature on the neighbourhood street network configuration in Turkish cities and provides insights into the challenges of developing countries, as the limited literature on the environment-obesity link is dominated by the North American and Australian 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. Interventions and policies aimed to increase direct (reduced direction changes) and dense (relatively shorter distances between intersections) connections between origins and destinations (e.g. home and commercial land-uses) within 10 to 20 minutes of walking around homes and schools may be a key to promoting active lifestyles and reducing BMIs among children. Moreover, planners and policy makers can use the analytical methodology applied in this study to provide targeted interventions rather than blanket solutions for the design of neighbourhoods in promoting active lifestyles among children.

Some of the limitations of this study are related to limited sample size and number of environmental and behavioural attributes included. Few older children (age 16) attended the study, which might yield to biased results on the relationship between obesity and age. Future work will address the expansion of the sample size and the inclusion of a wider range of variables, including but not limited to pedestrian environment features around homes as well as dietary habits. Another limitation is the bias of asking a few similar questions to both parents and children regarding children's physical activity levels, but there were rarely discrepancies between their answers. Other limitations include the preclusion of inferring causal relations and generalizable conclusions based on the cross-sectional data as well as the limited number of survey questions regarding physical activity levels of children. Nevertheless, the quantitative information provided by this study strengthens the existing and increasingly extensive knowledge base that supports pedestrian-oriented policy by revealing the correlates of childhood BMI. Research has demonstrated that providing walkable environments can lead to an increase in physical activity (Davison and Lawson 2006). However, the current study suggests that walkable neighbourhoods also support reduced childhood BMI. The next step in research is to investigate how various street-level environmental features and dietary habits influence physical activity levels among children if we are to create walkable environments encouraging physical activity.

5. Conclusion

This study provides important evidence for planners, urban designers, policy makers and practitioners on the significant associations of built environment, in general, and street network configuration, in particular, within home- and school-environments. The results show that street network design is a significant environmental determinant of childhood BMI and walking behaviour. Although it is very hard to change the existing street layout in currently built neighbourhoods, in the design process of new school areas as well as in the regeneration of the existing neighbourhoods, planners need to design a well-connected street network with relatively denser connections and reduced direction changes. This would increase accessibility by reducing the distances children need to walk within their neighbourhoods and between home and school. A continuous street network within the neighbourhood – not only within the immediate context (a couple of blocks) of homes and schools but also within their larger fabric (800-1600mt buffers or 10-to-20-minute walking distance) – is also the key to increasing walking among children. Based on the findings presented in this study some lessons can be drawn for practitioners with regard to quality of urban life. One practical implication of the findings presented in this study would be the provision of more generous sidewalks and increased number of street trees on spatially more prominent streets. Those streets, which contribute critically to the larger urban context (to the long-distance connections), need to be treated and designed strategically. One rule of thumb could be to expand sidewalks along these relatively more accessible segments by reducing on-street parking, where possible. This would encourage walking among school children, leading to increased pedestrian movement en route to schools. This would help alleviate one of the primary concerns of parents, as identified in the parental surveys which indicate that many parents do not allow their children to walk to/from school due to the lack of other children walking. Another concern raised in both children's and parents' surveys regarding active commuting to/from school is relatively long distances between home and school. This finding highlights the importance of distance in school-siting decisions. Policy-makers need to begin explicitly considering access to schools in planning decisions, which would encourage schools to be located within acceptable walking distances in neighbourhoods. Based on the results of this study, 800-to-1600 meters should be considered as the threshold beyond which active commuting to/from school would be unfeasible. More empirical research is needed to inform school-siting policies that would encourage children and parents to walk to/from schools. This, in return, would lead to reduced rates of childhood BMI.

Acknowledgments

Removed for review purposes.

References

Adkins, A., Dill, J., Luhr, G. and Neal, M., 2012. Unpacking walkability: testing the influence of urban design features on perceptions of walking environment attractiveness. *Journal of Urban Design*,. Routledge 17(4), 499–510.

Akbay, C. and Boz, I., 2005. Kahramanmaraş’ta ailelerin ev ve ev dışı gıda tüketim talebi ve tüketici davranışlarının ekonomik analizi. *KSU Journal of Science and Engineering*, 8(1), 122–131.

Asadi-Shekari, Z., Moeinaddini, M., Aghaabbasi, M., Cools, M. and Shah, M. Z., 2019. Exploring effective micro-level items for evaluating inclusive walking facilities on urban streets (applied in Johor Bahru, Malaysia). *Sustainable Cities and Society*, 49, 101563.

Bahrainy, H. and Khosravi, H., 2013. The impact of urban design features and qualities on walkability and health in under-construction environments: The case of Hashtgerd new town in Iran. *Cities*, 31, 17–28.

Baran, P. K., Rodríguez, D. A. and Khattak, A. J., 2008. Space Syntax and walking in a new urbanist and suburban neighbourhoods. *Journal of Urban Design*,. Taylor & Francis Group 13(1), 5–28.

Bodea, T., Garrow, L., Meyer, M. and Ross, C., 2008. The influence of socio-demographic and built environment characteristics on the likelihoods of being overweight and obese: a cautionary tale. *Transportation*, 35, 179–199.

Brown, B. B., Smith, K. R., Hanson, H., Fan, J. X., Kowaleski-Jones, L. and Zick, C. D., 2013. Neighborhood design for walking and biking: Physical activity and body mass index. *American Journal of Preventive Medicine*,. Elsevier Inc. 44(3), 231–238.

Carroll-Scott, A., Gilstad-Hayden, K., Rosenthal, L., Peters, S. M., McCaslin, C., Joyce, R. and Ickovics, J. R., 2013. Disentangling neighborhood contextual associations with child body mass index, diet, and physical activity: the role of built, socioeconomic, and social environments. *Social Science & Medicine*, 95, 106–114.

Carver, A., Barr, A., Singh, A., Badland, H., Mavoa, S. and Bentley, R., 2019. How are the built environment and household travel characteristics associated with children’s active transport in Melbourne, Australia?. *Journal of Transport & Health*,. Elsevier 12, 115–129.

Cerin, E., Saelens, B. E., Sallis, J. F. and Frank, L. D., 2006. Neighborhood environment walkability scale: Validity and development of a short form. *Medicine and Science in Sports and Exercise*, 38(9), 1682–1691.

Chiaradia, A., 2007. Emergent route choice behaviour, motorway and trunk road network: the Nantes conurbation. in *6th International Space Syntax Symposium*,.

Cooper, A. R., Page, A. S., Foster, L. J. and Qahwaji, D., 2003. Commuting to school: Are children who walk more physically active?. *American Journal of Preventive Medicine*, 25(4), 273–276.

Davison, K. K. and Lawson, C. T., 2006. Do attributes in the physical environment influence children's physical activity? A review of the literature. *International journal of behavioral nutrition and physical activity*, 3(1), 19.

Davison, K., L Werder, J. and Lawson, C., 2008. Children's active commuting to school: current knowledge and future directions. *Preventing chronic disease*, 5(3).

Ding, D., Sallis, J. F., Kerr, J., Lee, S. and Rosenberg, D. E., 2011. Neighborhood environment and physical activity among youth: a review. *American journal of preventive medicine*, 41(4), 442–455.

Discigil, G., Tekin, N. and Soylemez, A., 2009. Obesity in Turkish children and adolescents: prevalence and non-nutritional correlates in an urban sample. *Child: care, health and development*, 35(2), 153–158.

Durand, C. P., Andalib, M., Dunton, G. F., Wolch, J. and Pentz, M. A., 2011. A systematic review of built environment factors related to physical activity and obesity risk: implications for smart growth urban planning. *Obesity Reviews*, 12(5), 173–182.

Farajian, P., Panagiotakos, D. B., Risvas, G., Karasouli, K., Bountziouka, V., Voutzourakis, N. and Zampelas, A., 2013. Socio-economic and demographic determinants of childhood obesity prevalence in Greece: The GRECO (Greek Childhood Obesity) study. *Public Health Nutrition*, 16(2), 240–247.

Forsyth, A., Hearst, M., Oakes, J. M. and Schmitz, K. H., 2008. Design and destinations: factors influencing walking and total physical activity. *Urban Studies*, 45(9), 1973–1996.

Frank, L., Engelke, P. and Schmid, T., 2003. *Health and community design: The impact of the built environment on physical activity*. Edited by Island Press.

Frederick, C. B., Snellman, K. and Putnam, R. D., 2014. Increasing socioeconomic disparities in adolescent obesity. *Proceedings of the National Academy of Sciences*, 111(4), 1338–1342.

Hillier, B. and Iida, S., 2005. Network and Psychological Effects in Urban Movement. in Cohn, A. G. and Mark, D. M. (eds) *Spatial Information Theory*,. Springer Berlin Heidelberg 475–490.

Hillier, B., Penn, A., Hanson, J., Grajewski, T. and Xu, J., 1993. Natural movement: or, configuration and attraction in urban pedestrian movement. *Environment and Planning B: Planning and Design*,. PION LTD 20(1), 29–66.

Hillier, B., Yang, T. and Turner, A., 2012. Normalising least angle choice in Depthmap - and how it opens up new perspectives on the global and local analysis of city space. *Journal of Space Syntax*,. University College London 3(2), 155–193.

Himes, C. L. and Reynolds, S. L., 2005. The changing relationship between obesity and educational status. *Gender Issues*, 22(2), 45–57.

Huang, R., Moudon, A. V, Cook, A. J. and Drewnowski, A., 2015. The spatial clustering of obesity: does the built environment matter?. *Journal of human nutrition and dietetics : the official journal of the British Dietetic Association*, 28(6), 604–12.

Kant, A. K. and Graubard, B. I., 2013. Family income and education were related with 30-year time trends in dietary and meal behaviors of American children and adolescents. *Journal of Nutrition*, 143(5), 690–700.

Koohsari, M. J., Sugiyama, T., Mavoa, S., Villanueva, K., Badland, H., Giles-Corti, B. and Owen, N., 2016. Street network measures and adults' walking for transport: Application of space syntax. *Health & Place*,. Pergamon 38, 89–95.

Lamiquiz, P. J. and Lopez-Dominguez, J., 2015. Effects of built environment on walking at the neighbourhood scale. A new role for street networks by modelling their configurational accessibility?. *Transportation Research Part A: Policy and Practice*,. Pergamon 74, 148–163.

Larsen, H. K., Gilliland, J., Hess, P., Tucker, P., Irwin, J. and He, M., 2009. The influence of the physical environment and sociodemographic characteristics on children’s mode of travel to and from school. *American Journal of Public Health*, 99(3), 520–526.

Law, S., Chiaradia, A. and Schwander, C., 2012. Towards a multi-modal space syntax analysis. A case study of the London street and underground network. in *8th International Space Syntax Symposium*, 8021–1–8021–20.

Loureiro, M. L. and Nayga, R. M., 2006. Obesity, weight loss, and physician’s advice. *Social Science & Medicine*, 62(10), 2458–2468.

Marshall, W. E., Piatkowski, D. P. and Garrick, N. W., 2014. Community design, street networks, and public health. *Journal of Transport & Health*, 1(4), 326–340.

McCormack, G. R. and Shiell, A., 2011. In search of causality: a systematic review of the relationship between the built environment and physical activity among adults. *International Journal of Behavioral Nutrition and Physical Activity*, 8(1), 125.

Miranda, M. L., Edwards, S. E., Anthopolos, R., Dolinsky, D. H. and Kemper, A. R., 2012. The built environment and childhood obesity in Durham, North Carolina. *Clinical Pediatrics*, 51(8), 750–758.

Ozbil, A., Argin, G. and Yesiltepe, D., 2016. Pedestrian route choice by elementary school students: the role of street network configuration and pedestrian quality attributes in walking to school. *International Journal of Design Creativity and Innovation*, 4(2), 67–84.

Ozbil, A. and Peponis, J., 2011. Understanding how street connectivity affects pedestrian flows. *Urban Design International*, 16(2), 125–141.

Oztora, S., 2005. *İlköğretim çağındaki çocuklarda obezite prevalansının belirlenmesi ve risk faktörlerinin araştırılması*.

Peponis, J., Ross, C. and Rashid, M., 1997. The structure of urban space, movement and co-presence: the case of Atlanta. *Geoforum*, 28(3), 341–358.

Pikora, T., Giles-Corti, B., Bull, F., Jamrozik, K. and Donovan, R., 2003. Developing a framework for assessment of the environmental determinants of walking and cycling. *Social Science & Medicine*,. Pergamon-elsevier Science Ltd 56(8), 1693–1703.

Rahman, T., Cushing, R. A. and Jackson, R. J., 2011. Contributions of built environment to childhood obesity. *Mount Sinai Journal of Medicine: A Journal of Translational and Personalized Medicine*, 78(1), 49–57.

Riazi, N. A. and Faulkner, G., 2018. Children's Independent Mobility. in *Children's Active Transportation*,. Elsevier 77–91.

Rodríguez, D. A., Brisson, E. M. and Estupiñán, N., 2009. The relationship between segment-level built environment attributes and pedestrian activity around Bogota's BRT stations. *Transportation Research Part D: Transport and Environment*, 14(7), 470–478.

Roth, M. A., Millett, C. J. and Mindell, J. S., 2012. The contribution of active travel (walking and cycling) in children to overall physical activity levels: A national cross sectional study. *Preventive Medicine*,. Elsevier Inc. 54(2), 134–139.

Sallis, J. F. and Glanz, K., 2006. The role of built environments in physical activity, eating, and obesity in childhood. *The future of children*, 16(1), 89–108.

Şık, B., 2017. *Çocukluk Çağı Obezitesi Raporu*.

Sturm, R., 2005. Childhood obesity -- what we can learn from existing data on societal trends, Part 2. *Preventing chronic disease*,. 2005/03/15 edn. 2005/03/15.: Centers for Disease Control and Prevention 2(2), 1–9.

Süzek, H., Arı, Z. and Uyanık, B. S., 2005. Muğla'da yaşayan 6-15 yaş okul çocuklarında kilo fazlalığı ve obezite prevalansı. *Türk Biyokimya Dergisi*, 30(4), 290–295.

Turner, A., 2007. From axial to road-centre lines: A new representation for space syntax and a new model of route choice for transport network analysis. *Environment and Planning B: Planning and Design*, 34(3), 539–555.

Untermann, R. K., 1984. *Accommodating the pedestrian: Adapting towns and neighbourhoods for walking and bicycling*.

Wang, Y. and Beydoun, M., 2007. The obesity epidemic in the United States—gender, age, socioeconomic, racial/ethnic, and geographic characteristics: a systematic review and meta-regression analysis. *Epidemiologic reviews*, 29(1), 6–28.

Wood, S. L., Demougin, P. R., Higgins, S., Husk, K., Wheeler, B. W. and White, M., 2016. Exploring the relationship between childhood obesity and proximity to the coast: A rural/urban perspective. *Health & Place*, 40, 129–136.

World Health Organization, 2007. *Growth reference data for 5-19 years*. Geneva.