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A dose–response effect between built environment characteristics and transport walking for youths

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ABSTRACT

Background: A lack of physical activity can lead to long-term health problems for youths (aged 5–18) worldwide. Built environment characteristics are increasingly being recognized as important factors affecting transport walking, a reliable source of overall physical activity for youths. However, the relationship between built environment characteristics, especially residential density, and youths' walking for transport purposes (transport walking) remain largely inconclusive, due to limited variation in built environment variables and an assumption of linear association.

Methods: In this study, we explore the dose-response relationship between built environment characteristics and transport walking for youths in Hong Kong, a city with large variations in residential density. Detailed transport walking behaviors, such as the number of trips and walking duration, were extracted from the 2011 Hong Kong Travel Characteristics Survey (N = 13,287; aged 5–18). Neighborhood socioeconomic status, age, gender, household income, and household vehicle ownership were controlled in the generalized additive mixed models (GAMMs) of the built environment-transport walking associations.

Results: We found inverted U-shaped associations between population density and both the odds and total minutes of transport walking. Population density within 30,000–60,000 persons/km^2 is optimal to promote transport walking for youths. In addition, the number of recreational facilities and retail shops were positively associated with likelihood of engaging in transport walking, and number of bus stops was negatively associated with transport walking.

Conclusion: We add new empirical evidence on the significant and non-linear relationship between urban density and transport walking. Although increasing urban density in already densely developed cities may not be an effective intervention strategy to increase transport walking in youths, such strategy may still be effective in other less dense areas.

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1. Introduction

Being sufficiently physically active is important for youths (children and adolescents 5–18 years old), as it is associated with a wide range of health benefits, such as reduced cardiovascular risk factors, enhanced bone mineral density, and improved physical and psychological well-being (Janssen and Leblanc, 2010; Strong et al., 2005). The World Health Organization recommends that children and adolescents should be physically active at a moderate or vigorous level for at least 60 min a day. However, more than 80% of the world's adolescent population is insufficiently physically active (World Health Organization, 2018). Consequently, stimulating youths' physical activity is a crucial part of health strategies of many governments.

Walking for transport purposes (i.e. transport walking) is a reliable source of overall physical activity: there is consistent evidence that youths who walk or cycle to school or other destinations report significantly higher levels of physical activity than those who travel by motorized vehicles (Faulkner et al., 2009; Lubans et al., 2011; van Sluijs et al., 2009). Walking can offer additional environmental benefits, such as improved air quality and decreased traffic congestion and carbon emissions if more people use walking and cycling instead of cars (Nieuwenhuijsen, 2016; Xiao et al., 2017). Walking is the most common form of physical activity, and it can be conveniently done alone or with others. Increasing brisk walking is one of the most reliable and feasible interventions to help children and adolescents to achieve their recommended levels of physical activity (Carlin et al., 2016; Mitra, 2013; Saelens and Handy, 2008). Transport walking has thus recently attracted huge attention from policymakers and researchers.

Built environment is increasingly being recognized as an essential factor that can promote or hinder transport walking. Understanding the built environment–transport walking associations is vital for children and adolescents who have fewer choices of transportation mode and hence are more likely to be affected by the environment (D'Haese et al., 2015; Ding et al., 2011). Empirical findings regarding built environment and transport walking reveal complex patterns, with inconsistent associations for some built environment characteristics.

There is strong evidence for positive associations between recreational facility accessibility and transport walking for youths. In a neighborhood with nearby parks, recreational or sports facilities, and commercial stores, youths are likely to travel to these destinations by foot and tend to make more transport walking trips. Three reviews examining transport walking or cycling for children and adolescents concurred that the provision of parks or other recreational facilities had positive effects on transport walking rates and overall level of physical activity (Ding et al., 2011; J. Panter, Jones and van Sluijs, 2008; Pont et al., 2009). For example, in a survey of 678 children (ages 6–12) in two American cities (Kurka et al., 2015), children living in areas with less access to recreational facilities or parks reported 13 fewer minutes of accelerometer-measured moderate to vigorous physical activity per day (MVPA) than those living in areas with higher access. Children who were aware of more sport and recreational facilities were more likely to walk to school or to other destinations than those who were less aware (Evenson et al., 2006). Similar results were reported in a longitudinal study in Hong Kong: adolescents' MVPA levels were positively associated with perceived availability of sports facilities in neighborhoods after a 16-month follow-up (Wong et al., 2014). Alternatively, those findings might be interpreted that the youths become aware of more facilities because walking to school increase their exposure to those facilities.

There are mixed results about the association between land-use mix and transport walking for youths (D'Haese et al., 2015; Ding et al., 2011; J. Panter et al., 2008; Pont et al., 2009). Urban areas with higher levels of land use diversity may increase the proximity to and accessibility of different types of destinations and make transport walking more feasible. However, some studies have reported insignificant associations between land-use mix and transport walking (Mitra et al., 2010; J. R. Panter, Jones, Van Sluijs and Griffin, 2010; Yarlagadda and Srinivasan, 2008).

Residential density is important for planning purposes because it is easy to measure from census and other data, and it is regulated by many governments (Forsyth et al., 2007). Residential density may have direct effects on transport walking and indirect effects as a proxy for other variables such as socioeconomic status (SES) (Forsyth et al., 2007). It has been suggested that areas with higher residential density have more destinations such as shops, services, and public transport stops nearby and that they therefore promote transport walking (Forsyth et al., 2007; C. Lee and Moudon, 2006). Some have argued that density is a proxy variable for other dimensions such as low-income populations, land-use mix, and transit use (Cervero and Kockelman, 1997; Handy et al., 2002; C. Lee and Moudon, 2004).

However, findings on the associations between residential density and transport walking or overall physical activity for youths remain largely inconclusive. Reviews based on studies conducted in low density cities, especially the United States and Australia, found mostly positive associations between residential density and transport walking (Ding et al., 2011; J. Panter et al., 2008; Pont et al., 2009). A recent study conducted in Nanjing, a high-density city in China, reported that residential density was negatively associated with self-reported recreational physical activity time for 2375 high school students (Xu et al., 2010). Another study found that children living in rural neighborhoods engaged in more physical activity than those living in urban neighborhoods (Sandercock et al., 2010). However, these two studies focused on the outcomes of overall physical activity rather than transport walking, and the two may have different associations with built environment factors (Ding et al., 2011; Saelens and Handy, 2008).

Furthermore, social environment and safety are other factors affecting youth's transport walking. Children who reported higher perceived safety were more likely to use alternate routes to and from school, which suggests that perceived safety of the environment may encourage children to actively explore their environment (Sun et al., 2018a,b). General safety and traffic safety were associated with transport working in North America and Australia, but not in Europe (D'Haese et al., 2015). This might be due to the increased dangers of walking and cycling to school in the US and Australia, because of substantial urban sprawl (Rothman et al., 2015). Children who walked or cycled to school also tended to explore spaces when they traveled independently (Sun et al., 2018a,b). Studies on independent mobility suggested that children who had the freedom to play outdoors and traveled actively without adult supervision accumulated more physical activity than others (Schoeppe et al., 2013).

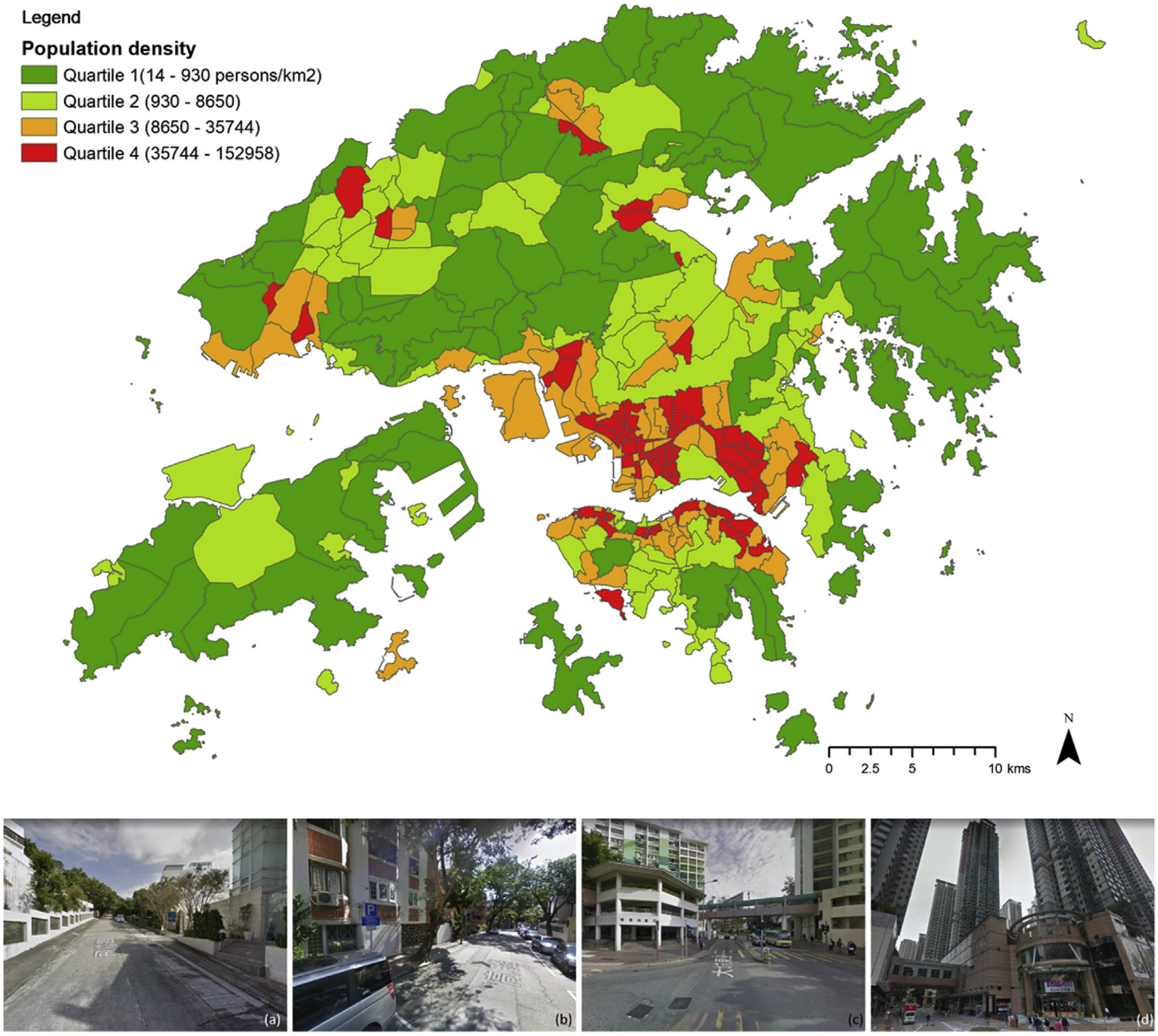

Fig. 1. There are great variations in urban density in Hong Kong. Up: Four quartiles of population density of administrative unit—Tertiary Planning Units (TPUs) in Hong Kong. Below: Examples of low—quartile 1 (a), medium-low—quartile 2 (b), medium-high—quartile 3 (c), and high—quartile 4 (d) density developments in Hong Kong. Source: Google Inc.

A major challenge to determining built environment–transport walking associations is the limited variation in built environment factors, especially urban density. Most transport walking studies focusing on youths have been conducted in North America, Australia, and Europe, all of which feature relatively low urban density compared with some cities in Asia. The lack of adequate variation in urban density prevents these findings from being generalized to densely developed cities. Hong Kong, for example, has a gross population density of 6000 persons/km^2. The population density in built-up areas is four times as high as gross density, because more than 75% of the land has been preserved as country parks or other natural areas. Hong Kong thus has considerable variation in urban density, ranging from areas with single-family houses to those with clusters of high-rises (Fig. 1). The quartile cut-off points (930, 8650, 35744 persons/km^2) for population density of administrative units in Hong Kong—Tertiary Planning Units (TPUs)—also supported great variation.

There is another caveat in the literature. Most empirical studies have used various linear models to estimate the built environment–physical activity associations. Recent studies have called for the estimation of complex dose-response relationships to identify the minimum, maximum, and optimal doses of built environment variables for promoting physical activity (Cerin et al., 2018; Christiansen et al., 2016; Kerr et al., 2016). One international study compared 12,181 adults in 10 countries and found a significant non-linear relationship between resident density and transport walking for adults (Christiansen et al., 2016). The authors of that study found that the relationship had an inverted U-shape with a threshold of 12,000 dwellings/km^2 for the maximum likelihood of transport walking. A further increase in residential density was associated with a decreased likelihood of transport walking. However, the dose-response relationship between the built environment and physical activity for youths is still unknown.

To address these research gaps, in this study we explore the dose-response relationship between the built environment and transport walking using a large sample of youths in Hong Kong.

2. Methods

2.1. Participants and walking data

Hong Kong is in the southeast coastal area of China. It has a total population of 7.3 million people and a land area of 1104 km^2, making it one of most densely populated cities in the world.

The walking data were obtained from the 2011 Hong Kong Travel Characteristics Survey (TCS). TCS was conducted by Transport Department to determine the overall travel behaviors in Hong Kong. TCS used a random sampling method to select participating households from a list of permanent dwelling addresses maintained by the Census & Statistics Department. The survey included a total of 101,385 participants of 35,401 households. The survey response rate was 71%. The present study comprised a geocoded sample of 13,287 youths between the ages of 5 and 18 randomly distributed throughout Hong Kong. The general trip information for a 24-h period for the participants was collected via face-to-face interviews. The participants needed to report in chronological order the places they have visited during the reference 24-h period as well as detailed transport modes, address of trip origin and destination, departure time and arrival time for all trips. Residence location, household income, household vehicle ownership and individual information (e.g. age, and sex, whether a full-time student) were also collected during the interviews.

Personal, household, trip data were combined via unique household and household member IDs. The total walking time in mins of a youth participant was calculated by summing up all walk components from trip data. Ethical approval for this study was granted by the Research Committee of City University of Hong Kong (H000691).

2.2. Environmental variables

Each participant's dwelling address was geocoded with ArcGIS 10.5 (Esri, U.S.A.). Two street network buffers (500 m and 1 km) were created around a dwelling location, consistent with a dose-response study for adults (Christiansen et al., 2016). Some potential walking-influencing built environment factors within the buffers were objectively calculated in GIS because of their relevance to walking behaviors and data availability: population density (Li et al., 2005); street connectivity (Adkins et al., 2012; Chin et al., 2008; Li et al., 2005); land-use mix; number of bus stops (Yang et al., 2019a), retail shops and recreational facilities; and distance to the closest Mass Transit Rail (MTR) station (Hajna et al., 2015; I. M. Lee et al., 2012). All built environment data were obtained from the Lands Department and Census & Statistics Department of Hong Kong.

Population density was defined as the residential population per unit of land area in Tertiary Planning Units (TPUs) in Hong Kong. Street connectivity was assessed by street intersection density, defined as the number of intersections (three or more streets) per unit of land area in buffers.

Land-use mix entropy score was calculated using the entropy score to measure the level of diversity of land use types. We measured destination or service diversity from number of residents and jobs in different categories; those data were maintained by Census & Statistics Department. It is different from previous land-use mix measures with land use categories (e.g. residential, commercial, or industrial levels) at the parcel level (Frank et al., 2005). The abstract land use at the parcel level is unable to capture the variations in high-density environments with intense and dominant mixed-use developments. The number of residents and the jobs belonging to different sectors (retail, accommodation, and all other jobs) were used to calculate the entropy score as a proxy for land-use mix in TPUs. Land-use mix $= (-1) \times [(b1/a) \times \ln(b1/a) + (b2/a) \times \ln(b2/a) + (b3/a) \times \ln(b3/a) + (b4/a) \times \ln(b4/a)]/\ln(n4)$, where b1 = number of residents, b2 = number of retail jobs, b3 = number of accommodation jobs, b4 = number of other jobs, a = sum of residents and jobs, and n4 = between 0 and 4 depending on the number of land-use types present.

2.3. Covariates

The survey also collected some personal-level data, which were used as covariates in this study: age, gender, household income, and household vehicle ownership. The monthly household income data were originally coded into 16 bands but were converted to 4 bands (< HKD10,000, HKD10,000–20,000, HKD20,000–30,000, and > HKD30,000). Age was converted to a 4-band variable (5–8, 9–11, 12–14, and 15–18 years).

The median household income (in HKD/month) in a participant's administrative planning unit (TPU) were used to assess neighborhood-level SES.

2.4. Data analysis

Descriptive statistics for the two walking outcome variables, namely any walking and total minutes of walking during the 24-h reference period, were computed for the whole group and the subgroups, respectively. The associations of built environment variables with walking outcomes were estimated using generalized additive mixed models (GAMMs) (Wood, 2017). GAMMs have been used in emerging public health studies (Cerin et al., 2018; Christiansen et al., 2016; Kerr et al., 2016). It can explain the clustering pattern of the walking behaviors for participants from the same administrative planning unit. Random intercepts were specified to account for within-administrative-unit clustering effects. More importantly, GAMMs can estimate complex dose-response

Table 1
Characteristics of participants responding to the main survey in analysis 1. The outcome variable was whether a participant engaged in any walking during the 24-h reference period (N = 13,287).

Individual characteristics	Number of participants	Percentage (%)	Engaged in walking (%)
All participants	13,287	100	45.3
Age (y)			
5-8	2867	21.6	54.2
9-11	2604	19.6	51
12-14	2992	22.5	40.5
15-18	4824	36.3	39.9
Gender			
Male	6909	52.0	45.9
Female	6378	48.0	44.7
Household income (HKD)			
Low(< 10 k)	1560	11.7	50.5
Medium-low (10–20 k)	4301	32.4	52.6
Medium-high (20–30 k)	2988	22.5	47.2
High (> 50 k)	4438	33.4	35.1
Vehicle ownership			
No	10,692	80.5	48.0
Yes	2595	19.5	34.1

relationships. The shape of the relationship was estimated with thin-plate splines. The criterion for the determination of a linear or non-linear relationship was whether the change in the Akaike information criterion (AIC) value was greater than 10.

A two-step data analysis was conducted for the walking variables: 1) GAMMs with binomial variance and a logit link function were used to model the likelihood of walking (versus not walking) for the 13,287 youths who responded to the main survey. The odds ratios of walking and 95% confidence intervals (CIs) were reported in the model. 2) GAMMs with negative binomial variance and logarithmic link function were used to model the total walking time for the subset of 6019 participants who walked at least once during the reference 24-h period. The regression coefficient β and 95% CIs estimated proportional increases in minutes of walking associated with changes in the environment variables.

The GAMM analysis was conducted in R with the “mgcv” package (Wood, 2017). Before implementing the GAMMs, Variance Inflation Factors (VIFs) were checked with the “usdm” package (Naimi et al., 2014), and all of the built environment variables with VIF ≥ 2 were removed to ensure no multicollinearity.

3. Results

3.1. Descriptive results

Table 1 describes the demographic and walking behaviors characteristics of a total number of 13,287 youths aged 5–18 years from the TCS. Overall, 45.3% of youths engaged in walking at least once during the 24-h period. Adolescents (12–14 and 15–18 years) were less likely to engage in walking than children (5–8 and 9–11 years). Male participants slightly outnumbered female participants and were slightly more likely to walk than females (45.9% vs 44.7%). Participants with high household income (> HKD50,000/month) were less likely to engage in walking than participants with lower income. Overall, 19.5% of participants living in households with private vehicles, and they were less likely to walk than those living in households without vehicles (34.1% vs 48%).

Table 2 describes the demographic and walking behaviors characteristics of 6019 youths walking at least once during the 24-h period. On average, the participants walked for 18.5 min (SD = 12.2). The adolescents (12–14 and 15–18 years) walked longer than children (5–8 and 9–11 years). There were slightly more male participants than female (51.4% vs 48.6%); male and female participants had similar walking time (18.6 vs 18.4 min). The participants with high household income (> HKD50,000) walked for shorter durations than other income groups. Youths living in households with vehicles also walked for shorter durations than those living in households without vehicles (15.3 vs 19.5 min).

3.2. Analysis 1: effects on odds of walking

In the first step analysis, the GAMM models were used to predict the likelihood of engaging in any walking for 13,287 youths. Street intersection density was removed from the GAMM models because it had a VIF > 2.

There are significant but non-linear associations between population density and the likelihood of walking in both 500-m and 1-km buffers (Fig. 2). The associations have a reverse U-shape that is positive up to a population density of 30,000 persons/km^2; it then becomes negative for higher population densities. The number of recreational facilities and the number of retail shops were positively and linearly associated with the odds of walking in both buffers, while land-use mix and distance to an MTR station were not significantly associated with this outcome (see Table 3). The number of bus stops was not associated with the likelihood of walking in the 500 m buffer, but it shows a negative association in the 1 km buffer.

Regarding the covariates, age, household income, and vehicle ownership were negatively associated with the likelihood of

Table 2
Characteristics of participants responding to the supplementary walking survey in analysis 2. The outcome variable was total walking time during the 24-h reference period (N = 6019).

Individual characteristics	Number of participants	Percentage (%)	Mean walking time in mins (SD)
All participants	6019	100.0	18.5 (11.2)
Age (y)			
5-8	1037	17.2	12.9 (9.4)
9-11	1026	17.0	14.6 (9.9)
12-14	1481	24.6	19.9 (11.1)
15-18	2475	41.1	21.6 (11.1)
Gender			
Male	3096	51.4	18.6 (11.2)
Female	2923	48.6	18.4 (11.2)
Household income (HKD)			
Low(< 10 k)	650	10.8	20.1 (11.3)
Medium-low (10–20 k)	1722	28.6	19.5 (11.3)
Medium-high (20–30 k)	1280	21.3	19.0 (10.6)
High (> 50 k)	2367	39.3	17.0 (11.2)
Vehicle ownership			
No	4601	76.4	19.5 (11.2)
Yes	1418	23.6	15.3 (10.4)

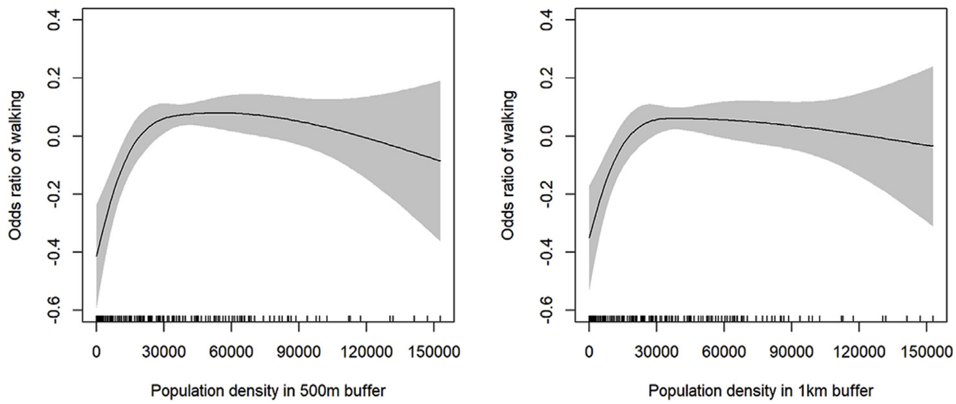

Fig. 2. The shape of the significant nonlinear associations between population density in the 500 m and 1 km street network buffers and the likelihood of walking during last 24-h reference period. The shaded area represents 95% confidence intervals. The tick marks above the x-axis represent the number of participants living in administrative planning units at this level of population density.

walking. Older children (9–11 years) and adolescents (12–14, 15–18 years) had lower likelihoods of walking compared with younger children (5–8 years). Youth from the highest income group (> HKD50, 000/month) had a lower likelihood of walking compared with those from the lowest income group (< HKD10, 000/month). Youth with a vehicle in their household had lower odds than those without. Male and female participants had no significant difference in their likelihood of walking.

3.3. Analysis 2: effects on total walking time

In the second step analysis, the GAMM models were used to predict total minutes of walking for those who walked at least once during 24-h period (N = 6019). Street intersection density was removed from the GAMM models because it had a VIF > 2.

Similar to the results of analysis 1, the association between population density and total walking time is significant but non-linear in both 500-m and 1-km buffers (Fig. 3). The associations have a reverse U-shape that is positive up to a population density of 60,000 persons/km^2, it then becomes negative for higher population densities. The number of retail shops was positively and linearly associated with total walking time in both buffers (see Table 4). The number of bus stops was negatively associated with total walking time. Land-use mix, the number of recreational facilities, distance to MTR were not significantly associated with total walking time.

Medium household income in neighborhood was negatively associated with total walking time. Compared with the age group of 5–8 years, the other three age groups walked for a significantly longer duration. There is no significant difference for male and female participants, or participants of different household income groups. Youth with a vehicle in their household walked significantly shorter duration than those without.

Table 3
The associations between built environment variables, neighborhood SES, and individual factors and likelihood of walking in analysis 1[b].

Model predictors	500 m buffer		1 km buffer	
	OR (95% CI)	p-value	OR (95% CI)	p-value
Built environment				
Population density	NA[a]		NA[a]	
Land-use mix	0.98 (0.91, 1.05)	0.49	0.97 (0.91, 1.04)	0.45
Number of recreational facilities	1.16 (1.09, 1.24)	< 0.01**	1.19 (1.09, 1.29)	< 0.01**
Number of retail shops	1.22 (1.12, 1.33)	< 0.01**	1.38 (1.24, 1.53)	< 0.01**
Distance to MTR	1.02 (0.96, 1.09)	0.48	1.04 (0.98, 1.12)	0.20
Number of bus stops	1.04 (0.95, 1.13)	0.42	0.88 (0.78, 0.99)	0.03*
Neighborhood SES				
Medium household income	0.95 (0.89, 1.01)	0.10	0.95 (0.89, 1.01)	0.08
Individual factors				
Age (y)				
5-8—Reference				
9-11	0.82 (0.72, 0.92)	< 0.01**	0.82 (0.72, 0.92)	< 0.01**
12-14	0.47 (0.42, 0.53)	< 0.01**	0.47 (0.42, 0.53)	< 0.01**
15-18	0.43 (0.39, 0.48)	< 0.01**	0.43 (0.39, 0.48)	< 0.01**
Gender				
Male—Reference				
Female	0.94 (0.87, 1.01)	0.10	0.94 (0.87, 1.01)	0.10
Household income (HKD/month)				
Low(< 10 k)—Reference				
Medium-low (10–20 k)	1.10 (0.96, 1.25)	0.17	1.10 (0.97, 1.25)	0.15
Medium-high (20–30 k)	0.90 (0.78, 1.04)	0.15	0.91 (0.79, 1.05)	0.18
High (> 50 k)	0.63 (0.54, 0.73)	< 0.01**	0.63 (0.54, 0.73)	< 0.01**
Vehicle ownership				
No–Reference				
Yes	0.77 (0.68, 0.86)	< 0.01**	0.76 (0.68, 0.86)	< 0.01**

[a] The association between population density and likelihood of walking was significant but not linear.
[b] All of the model predictors were entered into GAMM simultaneously. **p < 0.01.

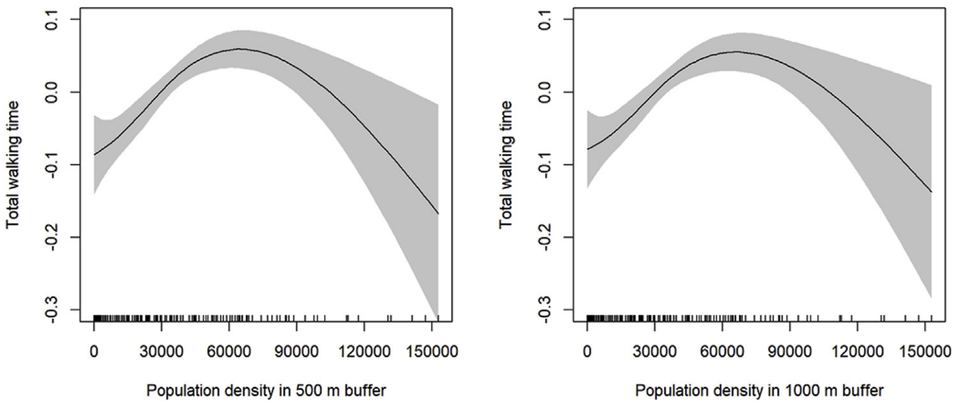

Fig. 3. The shape of the significant nonlinear associations between population density in the 500 m and 1 km street network buffers and the total minutes of walking during last 24-h reference period. The shaded area represents 95% confidence intervals. The tick marks above the x-axis represent the number of participants living in administrative planning units at this level of population density.

4. Discussion

In this study, we investigated the dose-response relationship between built environment characteristics and transport walking in a high-density city. We found significant but non-linear associations between population density and the odds and total minutes of transport walking. In addition, land-use mix was not associated with transport walking. The number of recreational facilities and retail shops was positively associated with the odds of engaging in transport walking; the latter was also positively associated with total minutes of walking. The number of bus stops was negatively associated with either the odds or total minutes of transport walking.

The travel characteristic data showed that 45.3% of youths engaged in walking at least once during the 24-h period. The walking rate is lower than that in a recent study in Hong Kong, which found 58% of its 1299 adolescents reported a weekly engagement in active commuting to school (Barnett et al., 2019). The measuring time scales (daily versus weekly) and behavior outcomes (walking

Table 4
The associations between built environment variables, neighborhood SES, and individual factors and total walking time for the participants in Analysis 2[b].

Model predictors	500 m buffer		1 km buffer	
	β (95% CI)	p-value	β (95% CI)	p-value
Built environment				
Population density	NA[a]		NA[a]	
Land-use mix	−0.01, (−0.04, 0.02)	0.55	−0.01, (−0.04, 0.02)	0.44
Number of recreational facilities	0.01, (−0.02, 0.04)	0.25	0.01, (−0.02, 0.03)	0.10
Number of retail shops	0.04, (0.01, 0.08)	0.01*	0.05, (0.01, 0.09)	0.01*
Distance to MTR	−0.01, (−0.03, 0.02)	0.59	−0.01, (−0.03, 0.02)	0.50
Number of bus stops	−0.07, (−0.10, −0.03)	< 0.01**	−0.06, (−0.10, −0.01)	0.01**
Neighborhood SES				
Medium household income	−0.05, (−0.07, −0.03)	< 0.01**	−0.05, (−0.07, −0.02)	< 0.01**
Individual factors				
Age (y)				
5-8—Reference				
9-11	0.11, (0.06, 0.16)	< 0.01**	0.11, (0.06, 0.16)	< 0.01**
12-14	0.43, (0.39, 0.48)	< 0.01**	0.43, (0.39, 0.48)	< 0.01**
15-18	0.55, (0.50, 0.59)	< 0.01**	0.55, (0.50, 0.59)	< 0.01**
Gender				
Male—Reference				
Female	0.01, (−0.02, 0.04)	0.65	0.01, (−0.02, 0.04)	0.63
Household income (HKD)				
Low(< 10 k)—Reference				
Medium-low (10–20 k)	−0.03, (−0.09, 0.02)	0.21	−0.03, (−0.09, 0.02)	0.22
Medium-high (20–30 k)	0.01, (−0.05, 0.07)	0.74	0.01, (−0.05, 0.07)	0.73
High (> 50 k)	−0.01, (−0.07, 0.06)	0.85	0.00, (−0.07, 0.06)	0.90
Vehicle ownership				
No—Reference				
Yes	−0.19, (−0.24, −0.14)	< 0.01**	−0.19, (−0.24, −0.14)	< 0.01**

[a] The association between population density and likelihood of walking was significant but not linear.
[b] All of the model predictors were entered into GAMM simultaneously. *p < 0.05, **p < 0.01.

versus active commuting) limit a further meaning comparison. Nevertheless, our results may have a higher degree of generalizability for the whole youth population in Hong Kong than those in the previous study, because this study have a larger sample size. The proportion of youths engaging in walking in Hong Kong is lower than that in Finland (Kallio et al., 2016), but are much higher than that in Canada (Gray et al., 2014) and in UK (Townsend et al., 2015).

4.1. *Urban density*

Urban density is a key planning parameter that heavily influences urban form and social and economic activities in cities. In this study, we revealed an inverted U-shaped dose-response effect between population density and odds of transport walking for 13,287 youths in 500 m and 1 km buffers after adjusting for other built environment factors. The population density was positively associated with the odds of transport walking up to a threshold of approximately 30,000 persons/km^2, after which the association became flat and then negative. Similarly, for 6019 youths walking at least once during 24-h period, the population density was positively associated with total minutes of transport walk up to a threshold of approximately 60,000 persons/km^2, after which the association rapidly became negative. The finding demonstrates the complex relationship between population density and transport walking. Our findings contrast with those in three reviews (Ding et al., 2011; J. Panter et al., 2008; Pont et al., 2009), which found a positive relationship between urban density and transport walking for youths. These three reviews mainly summarized findings from low density developed cities. In one empirical study, for example, children living in the neighborhoods in the top density tertile were three times more likely to walk or cycle compared to those living in lower density neighborhoods (Kerr et al., 2006). It is worth noting that in these study areas, the variation in population density was often limited, and the threshold level (30,000–60,000 persons/m^2) was typically not reached. Our finding that the negative association between urban density and transport walking time is in line with a study conducted in Nanjing, another densely developed city in China (Xu et al., 2010). Xu and his colleagues found that high school students living in areas in the higher tertile of residential density engaged in less recreational physical activity than those in areas in the lower tertile. One possible explanation is that both Hong Kong and Nanjing have great variation in urban density, although the two studies measured different domains of physical activity (transport walking vs recreational physical activity).

The inverted U-shaped dose-effect relationship between urban density and transport walking behaviors for youths identified in this study, is similar to a study for adults (Christiansen et al., 2016). However, for adults, dwelling density was positively associated with the likelihood of transport walking for adults up to 12,000 dwellings/km^2, beyond which further increases in dwelling density had little or negative influence (Christiansen et al., 2016). The threshold levels of urban density to increase the likelihood of transport walking for youths (30,000 persons/km^2, or 10,700 dwellings/km^2 given average household size of 2.8 in Hong Kong) and for adults

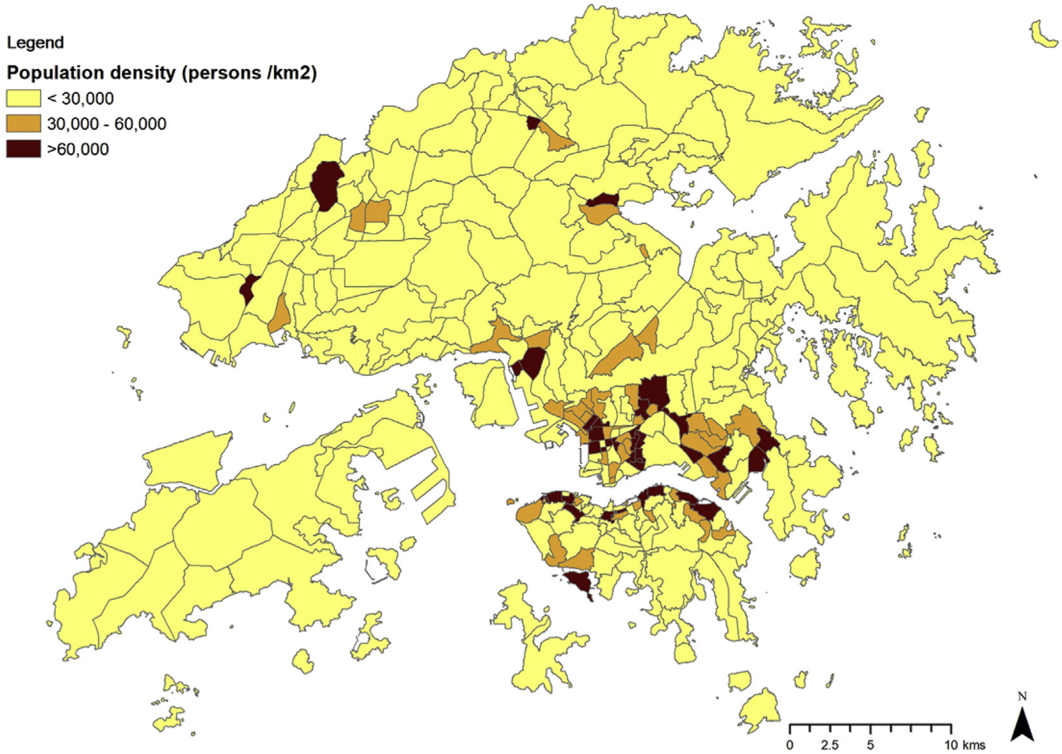

Fig. 4. The gross population density of administrative planning units—Tertiary Planning Units (TPUs) in Hong Kong. 84 out of 289 TPUs (or 29.0%) have a population density exceeding 30,000 persons/km^2 and 38 TPUs (13.1%) have one exceeding 60,000 persons/km^2. The extreme high-density developments in those areas may hinder youths' transport walking.

(12,000 dwellings/km^2) were close to each other. In addition, the present study provides new evidence of population density threshold of approximately 60,000 persons/km^2 to increase total minutes of walking for youths. Further studies are needed to find out whether these findings are sheer coincidence or generalizable. If the latter is true, our findings, together with others, should have significant planning implications. The threshold of approximately 30,000–60,000 persons/km^2 may become the maximum urban density level for urban development for the promotion of transport walking. Given that many urban areas in Hong Kong (Fig. 4) have exceeded this threshold, any future urban redevelopment may consider reducing urban density.

4.2. Land-use mix

In this study, we found that land-use mix was not associated with the likelihood of either transport walking or total transport walking time. This result contrasts with those in previous reviews (D'Haese et al., 2015; Ding et al., 2011; J. Panter et al., 2008; Pont et al., 2009) but is in line with previously reported insignificant associations for children (Mitra et al., 2010; J. R. Panter et al., 2010; Yarlagadda and Srinivasan, 2008) and adults in Hong Kong (Lu et al., 2017). The mixed results may derive from how land-use mix was measured. In the current study, we measured land-use mix with number of residents and jobs, rather than land use types (Frank et al., 2005). In densely developed cities, land use mixture in parcel level cannot capture the level of mix of different destinations and functions because most buildings have mixed uses, such as having retail shops on ground level and residential flats on upper levels. Some researchers have proposed to use jobs or points of interest to measure land-use mix for high-density cities (Lu et al., 2017; Sun et al., 2018a,b; Yang et al., 2019b; Wang et al., 2019). Future methodological development in assessing land-use mix, especially in high-density cities, is warranted to identify the optimal level of land-use mix to promote transport walking.

4.3. Accessibility of facilities

We also found that the number of recreational facilities in the buffers was positively associated with the likelihood of engagement in transport walking. The number of retail shops was positively associated with both the odds and total minutes of transport walking. The result concurs with previous reviews (D'Haese et al., 2015; Ding et al., 2011; J. Panter et al., 2008; Pont et al., 2009). Parks, sports and recreational facilities, and retail shops in neighborhoods are common destinations that are typically within walking distance. The accessibility of facilities makes transport walking feasible. The positive associations are relatively robust because they were reported in many studies across different locations. It is worth noting that the number of bus stop was negatively associated with transport walking in this study. More bus stops probably indicate heavier traffic flow, which may lead to concerns about traffic safety and reduce the likelihood of transport walking.

4.4. Strengths and limitations

This current study used a large sample size at the population level; hence, our results can be safely generalized to all youths in Hong Kong. The large variation in urban density in Hong Kong, in conjunction with the use of advanced statistic models, enables us to detect complex dose-response associations between built environment variables and transport walking. This study provides evidence that can be used to develop targeted interventions and planning policy for Hong Kong and for other densely populated urban areas in Asia, which are understudied in the public health literature. The tentative threshold level of population density (approximately 30,000 persons/km^2) for youths is close to that for adults (Christiansen et al., 2016); hence, the threshold level may be incorporated into international strategies to improve transport walking and public health upon verification by future studies.

This study has several limitations. This cross-sectional research design may prevent the identification of any causal relationship between built environment characteristics and transport walking. Future studies could use a quasi-experimental design, such as comparing behavioral changes before and after an environmental intervention (Carver et al., 2014; Hearst et al., 2012) or residential relocation (Boone-Heinonen et al., 2011; Mokhtarian and Cao, 2008), or comparing behaviors in large-scale public housing schemes in which residential relocation is largely determined by government agency rather than self-selection (Lu, 2018; Lu et al., 2018). Although the built environment was objectively measured in this study, transport walking behaviors were self-reported and thus subject to recall bias. To address this issue, walking data can be objectively assessed by accelerometers. It would be worth to explore the built environment-walking associations during school days and non-school days separately. However, we cannot conduct separate analyses due to limited information in the dataset. Lastly, this study was conducted in a single city, the ultra-high population density may influence the generalizability of the findings, and evidence from other high-density cities are needed to verify the robustness of our results.

5. Conclusion

Based on transport walking data from 13,287 youths aged 5–18 years old in Hong Kong, a high-density city but still with great variations in population density, the current study highlights the importance of accessibility to recreational facilities, such as parks, sports facilities and retail shops. More importantly, this study underscores the threshold effect of urban density on youths' likelihood of engaging in transport walking. Population density above 30,000–60,000 persons/km^2 has little or even negative effects on transport walking. Our findings suggest that neighborhoods with appropriate population density and easy access to pedestrian destinations have a positive effect on youths' transport walking, which is an important component of overall physical activity. In addition, although increasing density in high-density cities may not be an effective intervention strategy to increase transport walking for youths, such strategy may still be effective in other less dense areas.

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