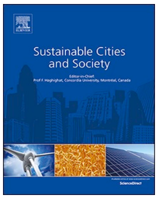
Sustainable Cities and Society 51 (2019) 101747

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs



Association between street greenery and walking behavior in older adults in Hong Kong

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ARTICLE INFO

Keywords:
Urban greenery
Google Street View
Walking
Older adults
Physical activity
Built environment

ABSTRACT

Built environment interventions, such as creating green and walkable neighborhoods have increasingly been recognized as an effective approach to promote physical activity and health for older adults. However, evidence of the associations of urban greenery and older adults' physical activity is still inconclusive, partially due to the difficulty to estimate eye-level urban greenery exposure. To address this gap, we assessed street greenery by Google Street View (GSV) images with machine learning techniques and associated it with walking behavior for 10,700 and 1083 Hong Kong older adults (aged 65 or above) respectively. Neighborhood socioeconomic status, individual factors, and other built environment characteristics were controlled for in the analysis. We found that street greenery assessed by GSV was positively associated with both the odds of engaging in walking and total walking time of the older adults. Our findings suggest that urban planners and policymakers should maximize residents' greenery exposure by considering the accessibility and visibility of urban greenery from pedestrian and human-scale perspectives.

1. Introduction

Population ageing is one of humanity's greatest challenges, as it will increase global economic and social demands. It is forecasted that by 2050, there will be about 1.5 billion people over the age of 65 globally (World Health Organization, 2011). The ageing trend is becoming a major concern in Hong Kong in particular. According to a recent census report, the median age of Hong Kong residents increased to 43.4 years old in 2017 from 39.6 years old in 2006, while the proportion aged 65 or above increased from 12 percent of whole population in 2006 to a new peak of 16 percent (Census and Statistics Department, 2016). The growing ageing population will cause rapidly increasing economic and social risk for countries and families, and among the greatest concerns is the sky-rocketing healthcare expenditure. For example, largely due to global aging, the annual cost associated with new cancer cases exceeded US$286 billion in 2009 and was projected to double by 2030 (World Health Organization, 2011).

There is strong evidence that regular physical activity provides primary and substantial health benefits to adults aged 65 and above (Chodzko-Zajko et al., 2009; Nelson et al., 2007; Pahor et al., 2014). The World Health Organization recommends that older adults should engage in at least 75 min of moderate to vigorous physical activity (MVPA) per week (World Health Organization, 2011). Compared with physically less active people, those who are more active have lower rates of all-cause mortality (Llamas-Velasco et al., 2016), lower risks of coronary heart disease (Batty, 2002; Soares-Miranda, Siscovick, Psaty, Longstreth, & Mozaffarian, 2016), high blood pressure (Hegde & Solomon, 2015), or type 2 diabetes (Tessier et al., 2000).

The initiatives of establishing health and aging-friendly cities call the attention from researchers, policymakers and urban planners to consider the relationship between built environment and physical activity level of older adults. Compared with younger adults, older adults tend to be more sedentary, make fewer and shorter trips, have smaller activity spaces (de Rezende, Rey-Lopez, Matsudo, & Luiz, 2014; Harvey, Chastin, & Skelton, 2015; Sjogren et al., 2014). Hence older adults are more liked to be exposed to and affected by surrounding built

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https://doi.org/10.1016/j.scs.2019.101747
Received 22 April 2019; Received in revised form 30 July 2019; Accepted 30 July 2019

environment (Barnett et al., 2017). However, previous evidence of the associations of urban greenery and older adults' physical activity is inconclusive, partially due to the difficulty to estimate eye-level urban greenery exposure.

To address this research gap, we assessed street greenery by Google Street View (GSV) images and a machine learning technique, and examined the association of street greenery and walking behaviors for 10,700 and 1083 older adults respectively after adjusting for other built environment and individual factors. Based on existing research findings, we hypothesized that street greenery measured by GSV images was positively associated with both the odds of walking and total walking time of older adults.

2. Literature review

2.1. Built environment and physical activity

Previous reviews conducted in Europe and North America found that older adults spent from 5.3 to 9.4 hours per day sedentary, equating to 65–80% of their waking time (de Rezende et al., 2014; Harvey et al., 2015; Sjogren et al., 2014). Compared with adults aged below 65, older adults spent more time on sitting in 32 European countries (Bennie et al., 2013). However, researchers found that physical activity level of older adults in the Hong Kong is higher than that of the younger population (Hui, Chan, Wong, Ha, & Hong, 2001). The tendency of older adults becoming more active was also reported in similar studies from Japan (Tsunoda et al., 2012), thus it is important to identify significant modifiable environmental factors to improve the physical activity level of older adults (Ferdinand, Sen, Rahurkar, Engler, & Menachemi, 2012; Zapata-Diomedi & Veerman, 2016). Compared with younger adults, fewer studies have explored the correlation between the built environmental factors and the physical activity for older adults (Moran et al., 2014). Older adults' physical activity has been suggested to be associated with built environment characteristics in a 3D framework, including urban density, street connectivity, and land use mix (Brownson, Hoehner, Day, Forsyth, & Sallis, 2009; McCormack & Shiell, 2011). In a systematic review, researchers identified the following built environmental factors associated with physical activity, including walkability, safety from crime, overall access to destinations and service, recreational facilities, public open space, commercial destinations, urban greenery and aesthetically pleasing scenery, walk-friendly infrastructure, and accessibility to public transportation (Barnett et al., 2017).

2.2. Greenery, physical activity and health

Urban greenery has received much research attention in relation to physical activity due to its potential for population level effects. Previous studies provided evidence that exposure to urban greenery is positively associated with physical activity and health outcomes of older adults, such as decrease the risk of high blood pressure (Hegde & Solomon, 2015), and type 2 diabetes (Tessier et al., 2000). For example, a study of 2168 Norwegian residents indicated that willingness to conduct physical activities in nature was positively associated with age (Calogiuri & Elliott, 2017). A study conducted in Netherlands also demonstrated that the relationship between greenspace and health outcome was stronger for the older adults (de Vries, van Dillen, Groenewegen, & Spreeuwenberg, 2013). A study with 15,672 participants in UK demonstrated that greener neighborhoods may protect the decline of physical activity in older adults (Dalton, Wareham, Griffin, & Jones, 2016). While in another study, researchers also suggested that presence of vegetation was positively related to older adults' walking (Van Cauwenberg et al., 2014).

However, evidence for the association between urban greenery and physical activity and health of older adults remains inconclusive, and further studies of the impact of greenness in older adults are warranted (Dalton et al., 2016; Van Cauwenberg et al., 2014). For example, a recent review of 42 studies estimating the association of the neighborhood built environment with walking in older adults, suggested that greenery and aesthetically pleasing scenery were not found to be associated with walking for transport purposes and within-neighborhood walking (Cerin et al., 2017).

There are several potential explanations of the inconsistent findings. It has been proposed that some older adults may engage in walking regardless urban greenery because they have no alternative transport options (Kerr et al., 2016). It is also possible that urban greenery may be a peripheral facilitator rather than an essential determinant of walking, for example, urban greenery may only affect walking when there are necessary conditions (i.e. accessible pedestrian destinations) for walking (Cerin et al., 2017).

2.3. New methods for measuring urban greenery

Another possible explanation may stem from different approaches to assess urban greenery. It should be noted that measuring residents' daily urban greenery exposure remains challenging. There are three major methods to assess urban greenery: questionnaires, field audits, and Geographic Information System (GIS) (Lu, Sarkar, & Xiao, 2018). Field audits are typically conducted by trained raters with standardized auditing instruments; both objective (i.e. number of trees) and subject aspects (i.e. level of maintenance) of urban greenery can be collected. Questionnaires are typically used in public health and urban studies to collect subjective aspects of urban greenery from local residents, such as perceived quantity, quality, and accessibility of parks or public green spaces. Both field audits and questionnaires, however, are time-consuming and labor-intensive hence often limited in terms of sample size or scale of study (Seresinhe, Preis, & Moat, 2017). GIS is typically used to generate objective measures of urban greenery, e.g. calculating the distance to parks or the percentage of greenness within a neighborhood. The GIS approach is more efficient than field audits and questionnaires. Some researchers used remote sensing techniques and satellite images in GIS to identify the amount of vegetation from an overhead view, using, for example, standardized indexes such as the Normalized Difference Vegetation Index (NDVI) (Leslie, Sugiyama, Ierodiaconou, & Kremer, 2010; Tilt, Unfried, & Roca, 2007). Some other researchers also use GIS to describe subjective aspects of the environment, which is often called qualitative GIS (Cope & Elwood, 2009).

Emerging urban big data and computer techniques allow researchers to determine urban greenery exposure using Google Street View (GSV) images (Li et al., 2015). GSV provides eye-level streetscape images in many global cities, directly matching what pedestrians perceive when walking through a city. Hence, it arguably may better represent residents' daily exposure to urban greenery than GIS measures typically based on an overhead view. GSV images have been used in several empirical studies (Li et al., 2015; Lu et al., 2018; Lu, Yang, Sun, & Gou, 2019; Seiferling, Naik, Ratti, & Proulx, 2017). Current studies mainly used the color of the pixels in images to identify the cover status of vegetation, yet green cars, exterior façades, or other artificial green objects may sometimes be confused as vegetation and cause false results.

To enhance the accuracy of extracting greenery from streetscape images, researchers have begun to explore the potential of advanced computer deep learning techniques (Helbich et al., 2019; Lu, 2018). Deep learning techniques such as fully convolutional neural networks (FCNN avoid the disadvantage of the color-based technique because they also consider the shapes of objects (Krizhevsky, 2014). The pyramid scene parsing network (PSPNet) is one of the most accurate deep learning techniques for identifying greenery from streetscape images, because it extends FCN by considering the global contextual information in images (Zhao, Shi, Qi, Wang, & Jia, 2017). In the present study, we used the PSPNet method to assess the level of street greenery in GSV images automatically, and associated street greenery with walking behaviors of older adults in Hong Kong.

3. Method

3.1. Study design

The walking data were extracted from 2011 Hong Kong Travel Characteristics Survey (HKTCS), which was conducted by the Transport Department of the Hong Kong Special Administrative Region (HKSAR) to explore the travel behaviors of Hong Kong residents. Face-to-face interviews were conducted between 2011–2012 by trained interviewers of Transport Department to collect participants' demographic data, household information and one-day travel records.

The main survey included 10,700 participants aged 65 and above, living throughout the whole city. The supplementary walking survey included 1083 participants aged 65 and above who performed walking at least once in the previous day. Participants of the main survey were asked to recall the trip mode choice for all trips in the previous day; those in the supplementary survey were asked to report detailed walking trip information including trip starting time and ending time. We identified whether a participant had done any walking trips or not from the main survey; and total walking time from the supplementary survey. All participants' dwelling locations were geocoded in ArcGIS based on their reported residential addresses. Conducting secondary analysis of HKTCS data was approved by the Research Ethics Committee of City University of Hong Kong (H001320).

3.2. Measure of urban greenery

In the present study, we measured urban greenery using GSV images and computer deep learning techniques. A residential neighborhood was defined as a circular buffer of 800 m around a participant's residential location (Saelens, Sallis, & Frank, 2003). Urban greenery and all other built environment variables were measured for the same buffer.

Street greenery was assessed using GSV images to measure the amount of eye-level greenery perceived by pedestrians (Fig. 1). Sampling points were created along all of the streets at a distance of 50 m, following previous studies (Li et al., 2015; Lu et al., 2018). Using a Python script that we developed, four streetscape images with a 90-degree field of view were retrieved for each point. The PSPNet we used was trained on the Cityscape dataset comprising 5000 streetscape images from 50 cities with pixelwise annotations (Cordts et al., 2016). The trained model can achieve an outstanding pixel-level accuracy of 93.4% in identifying vegetation, compared with manual extraction based on expert judgement (Zhao et al., 2017). Using the PSPNet method, the ratio of greenery pixels to total pixels of the four images was used to assess the level of street greenery for each point, as shown here: $Level\ of\ street\ greenery = \frac{\sum_{i=1}^{4} Greenery\ pixels_i}{\sum_{i=1}^{4} Total\ pixels_i}$. The average value for all GSV-generating points within the buffer of a participant's home was used to assess the level of street greenery in neighborhood.

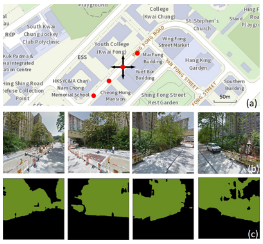

Fig. 1. Eye-level street greenery assessment with GSV method and the computer deep learning technique. (a) Sampling points with 50 m spacing were generated alone streets within an 800 m buffer around a participant's location. (b) Four GSV images with a 90-degree field of view were retrieved for each point with a Python script. (c) All of the street vegetation in the images was extracted with the PSPNet method.

The automated greenery extraction was validated using manual extraction. 100 GSV images were randomly selected. The street greenery in these images was manually extracted by a researcher using Adobe Photoshop. Result showed that the values of the GSV greenery extracted by the PSPNet method were highly correlated with those of the manual extraction, $r = 0.91$; $p < 0.01$, demonstrating the reliability of GSV greenery extraction method.

3.3. Other built environment factors and individual covariances

Some other activity-related built environment factors were calculated and adjusted in our models. These factors included population density (Barnett et al., 2017; Inoue et al., 2010), street intersection connectivity (Cerin et al., 2017; Grasser, Van Dyck, Titze, & Stronegger, 2013), number of pedestrian destinations (e.g. retail shops or recreational facilities) (Cerin et al., 2017; Grasser et al., 2013), land-use mix (Christiansen et al., 2016; Thornton et al., 2017), and distance to the closest Mass Transit Rail (MTR) station (Fenton, 2005). Population density was defined as the residential population per unit of land area in participant's neighborhood. Street intersection density was defined as the number of street intersections (three or more streets) per unit of land area. The land use mix, or entropy score, was calculated by measuring equal distributions of land use types. Three land use types were considered: residential, retail, and office. $Land\ use\ mix = (-1)\sum_i (p_i \ln(p_i))/\ln(3)$, where p_i was the share of specify land use of total land use. Population density data was obtained from Census and Statistics Department of Hong Kong, while all other built environment factors were calculated from the GIS data obtained from Land Department of Hong Kong.

The participants' individual factors (age in years, gender) and household income information were also included as potential confounding factors. These data were extracted from the main survey. The original 16-band household income was transformed into a 4-band categorical variable (< 10k-reference group; 10 to 20k, 20 to 30k, and > 30k HKD/month). The participants' ages were transformed into a 4-band categorical variable (65 to 69 years-reference group, 70 to 74 years, 75 to 79 years, and ≥80 years).

3.4. Data analysis

A two-step analysis strategy corresponding to the data structure of HKTCS was implemented: 1) the association was examined between urban greenery and the odds of walking (versus not walking) for the 10,700 older adults responding to the main survey, and 2) a second analysis were performed to explore the association between urban greenery and total walking time for the 1083 older adults responding to the supplemental survey.

In analysis 1, multilevel logistic regression models were used to explore the independent associations between urban greenness and the likelihood of walking after controlling for other built environment and individual covariates. In analysis 2, multilevel linear regression models were used to explore the independent association between urban greenery and the total walking time. For the both analyses, multilevel models were used to account for the clustering effect of walking behaviors in neighborhoods. Individual participants (level 1) were modeled to be clustered within street blocks (level 2) with random intercepts. Street blocks are census-defined aggregates in Hong Kong delineated for town planning purposes. Three models were successively carried out for both analyses. Model 1 only included urban greenery, model 2 additionally included other built environment variables and model 3 further included all individual covariates.

All the analyses were conducted using statistical software R (version 3.4) (R Core Team, 2014) with the lme4 package (version 1.1) (Bates, Mächler, Bolker, & Walker, 2015) for fitting and analyzing multilevel

Table 1
Descriptive statistics of all participants (Hong Kong SAR, China in 2011, N = 10,700).

Individual characteristics	Analysis 1 (N = 10,700)		Analysis 2 (N = 1083)	
	Count	Percentage (%)	Count	Percentage (%)
Age (years)				
65–69	3278	30.6	304	28.1
70–74	2757	25.8	283	26.1
75–79	2084	19.5	197	18.2
≥80	2581	24.1	299	27.6
Gender				
Male	5292	49.5	504	46.5
Female	5408	50.5	579	53.5
Household income				
Low (< 10k HKD)	4623	43.2	470	43.4
Medium-low (10–20k)	2510	23.5	264	24.4
Medium-high (20–30k)	1714	16	175	16.2
High (> 30k)	1853	17.3	174	16.1
Vehicle ownership				
No	9926	92.8	1012	93.4
Yes	774	7.2	71	6.6

models. Odds ratios (OR), 95% confidence intervals (CI), and standardized β were reported for the models.

4. Result

The descriptive statistics of all participants are shown in Table 1. There were slightly more female than male participants. A large proportion of participants had low household incomes (43.2% in analysis 1 and 43.4% in analysis 2), and overall, our participants had much lower incomes than the entire Hong Kong population (Census and Statistics Department, 2016). Only a small proportion of participants owned a private vehicle in their household (7.2% in analysis 1 and 6.6% in analysis 2). The private vehicle ownership for our participants is lower than that for overall population (17.5%) (Census and Statistics Department, 2016).

The descriptive statistics of walking behaviors, street greenery and the built environment characteristics are shown in Table 2. The average number of GSV-generating points in a neighborhood was 212.37 and 214.62 in analysis 1 & 2 respectively. The average street greenery value was 0.21, 0.20 in analysis 1 & 2 respectively. There is moderate seasonal fluctuation among the GSV images retrieved in this study, which may affect the level of vegetation extracted from these images. More GSV images were taken in winter (59.2%) than in spring (15.0%), summer (18.9%), or autumn (7.8%). However, the seasonal fluctuation of vegetation in Hong Kong is limited because street vegetation mostly comprises evergreens or semi-evergreens.

Table 2
Descriptive of street greenery and built environment characteristics and walking behaviors.

Variables	Analysis 1 (N = 10,700)		Analysis 2 (N = 1083)	
	Mean	SD	Mean	SD
Urban greenery				
Number of GSV sampling points	212.37	117.75	214.62	120.46
Street greenery	0.21	0.09	0.20	0.08
Built environment				
Population Density (persons/km2)	47978.00	32952.09	50823.55	33262.20
Land-use mix	0.54	0.28	0.54	0.27
Intersection Density (#/km2)	62.87	30.50	63.82	28.85
Number of retail shops (#/km2)	39.75	24.93	41.50	23.14
Number of recreational facilities (#/km2)	58.71	27.94	60.99	28.75
Distance to MTR (m)	924.68	1166.71	864.03	1078.90
Walking behaviour				
Percentage of older adults walked (%)	41.72			
Walking time (minutes)			17.40	17.20

Our participants' neighborhoods featured high population density, street intersection density, and land-use mix. In analysis 1, less than half of older adults (41.72%) walked at least once during the previous day. In analysis 2, the average total walking time was 17.40 min.

The results of the logistic regression models in analysis 1 are shown in Table 3. Street greenery was positively associated with the odds of walking after adjusting for covariates (OR [95% CI]: 1.206 [1.039, 1.400]).

Among the built environment factors, population density, the number of retail shops, and the distance to an MTR station were positively associated with the likelihood of walking after adjusting for the covariates. Intersection density was negatively associated with it. For individual factors, females had a higher likelihood of walking than males. Compared to the 65–69 years group, older participants had a higher likelihood of walking.

The results of the continuous regression models in analysis 2 are shown in Table 4. Street greenery was positively associated with total walking time in all three models: β [95% CI]: 0.202 [0.088, 0.316] in model 1, 0.201 [0.085, 0.318] in model 2, and 0.187 [0.071, 0.304] in model 3.

The number of recreation facilities was positively associated with total walking time in models 2 and 3. None of the other built environments were associated with total walking time. Medium-high (20–30k) household income was negatively associated with total walking time. None of the other individual factors were associated with total walking time.

5. Discussion

5.1. Major findings

This paper is one of the first studies to objectively measure eye-level greenery using big urban data of GSV in conjunction with a machine learning method, and to examine its relationship with the walking behavior of older adults. As hypothesized, eye-level greenery was associated with the odds of walking and total walking time for older adults. Our results show that with every increase of one standard deviation in street greenery, old adults' walking time rises by approximately 0.2 standard deviations. Our findings support the view that urban greenery has a positive and significant effect on walking (Barnett et al., 2017; de Vries et al., 2013; Moran et al., 2014). We believe that greener paths and streets may offer a more pleasant and comfortable environment for pedestrians (Calogiuri & Elliott, 2017). Walking, especially for transport purpose, e.g. to go to supermarkets, markets, or restaurants, is a major source of physical activity for older adults in Hong Kong (Cerin, Lee, Barnett, Sit, Cheung, Chan et al., 2013). Our results also support previous findings that the perceived greenery is a good predictor for walking behavior, because GSV images may capture what a pedestrian see and perceive on streets (Astell-Burt, Feng, & Kolt, 2014; Sarkar et al., 2015; Sugiyama & Ward Thompson, 2008).

We also found that the number of recreational facilities was positively associated with total walking time. In Hong Kong, recreation facilities are often located near large housing estates, and they cater to both children and the elderly, with children playgrounds, various sports courts, and elderly fitness facilities (Fig. 2). Previous studies also indicated that recreational facilities may facilitate overall walking for transportation (Saelens & Handy, 2008). In another study from Hong Kong, researchers also found that the diversity of recreational destinations were positively related to overall walking for transportation

Table 3
Multilevel logistic regression models for predicting the likelihood of walking vs. not walking (Hong Kong SAR, China, N = 10,700).

Model predictors	Model 1 OR, (95% CI), p-value	Model 2 OR, (95% CI), p-value	Model 3 OR, (95% CI), p-value
Urban greenery			
Street greenery	1.206, (1.039, 1.400), p = 0.014	1.169, (1.010, 1.353), p = 0.037	1.165, (1.004, 1.352), p = 0.044
Built environment			
Population density		1.113, (1.023, 1.210), p = 0.012	1.113, (1.022, 1.211), p = 0.013
Land use mix		0.981, (0.906, 1.062), p = 0.639	0.982, (0.906, 1.065), p = 0.661
Intersection density		0.848, (0.741, 0.971), p = 0.017	0.837, (0.730, 0.960), p = 0.011
Number of retail shops		1.648, (1.436, 1.891), p < 0.001	1.612, (1.402, 1.854), p < 0.001
Number of rec. facilities		0.919, (0.842, 1.004), p = 0.062	0.923, (0.844, 1.010), p = 0.081
Distance to MTR		1.116, (1.037, 1.201), p = 0.003	1.097, (1.018, 1.183), p = 0.015
Individual factors			
Age			
65–69—Reference			
70–74			1.306, (1.161, 1.468), p < 0.001
75–79			1.648, (1.446, 1.878), p < 0.001
≥80			2.508, (2.200, 2.858), p < 0.001
Gender			
Male—Reference			
Female			1.421, (1.299, 1.554), p < 0.001
Household income (HKD)			
Low(< 10k)—Reference			
Medium-low (10–20k)			1.030, (0.913, 1.162), p = 0.630
Medium-high (20–30k)			0.955, (0.832, 1.095), p = 0.509
High (> 30k)			0.859, (0.744, 0.992), p = 0.038
Vehicle ownership			
No—Reference			
Yes			0.696, (0.579, 0.836), p < 0.001
Model fitting-AIC	12862.64	12798.45	12503.08
Model fitting-Log likelihood	−6426.32	−6387.22	−6231.54

(Cerin, Lee, Barnett, Sit, Cheung, Chan et al., 2013). Recreation facilities provide a place for older adults not only to engage in physical activity but also to communicate with friends and maintain their social connections.

We found largely non-significant correlations between older adults' walk behaviors and objectively measured built environment factors in 3D framework, including population density, land use mix, and street intersection density (Brownson et al., 2009; McCormack & Shiell, 2011). Population density was positively associated with the odds of walking, while street intersection density was unexpected negatively associated with the odds of walking. None of these three factors was associated with total walking time. Our findings are in contrast to those

Table 4
Multilevel linear regression models for predicting walking time (Hong Kong SAR, China, N = 1,083).

Model predictors	Model 1 β, (95% CI), p-value	Model 2 β, (95% CI), p-value	Model 3 β, (95% CI), p-value
Urban greenness			
Street greenery	0.202, (0.088, 0.316), p = 0.001	0.201, (0.085,0.318), p = 0.001	0.187, (0.071, 0.304), p = 0.002
Built environment			
Population density		0.057, (-0.031,0.144), p = 0.205	0.067, (−0.020, 0.153), p = 0.129
Land use mix		0.027, (-0.061,0.116), p = 0.549	0.036, (-0.052, 0.124), p = 0.425
Intersection density		0.016, (-0.123,0.156), p = 0.819	0.046, (-0.090, 0.183), p = 0.507
Number of retail shops		−0.038, (-0.181,0.106), p = 0.606	−0.044, (−0.188, 0.100), p = 0.547
Number of rec. facilities		0.104, (0.001,0.207), p = 0.047	0.106, (0.003, 0.210), p = 0.043
Distance to MTR		0.037, (-0.042,0.116), p = 0.355	0.015, (−0.064, 0.095), p = 0.706
Individual factors			
Age			
65–69—Reference			
70–74			−0.058, (−0.212, 0.097), p = 0.465
75–79			−0.068, (−0.240, 0.104), p = 0.436
≥80			−0.138, (−0.293, 0.017), p = 0.081
Gender			
Male—Reference			
Female			0.054, (−0.055, 0.163), p = 0.328
Household income (HKD)			
Low (< 10k)—Reference			
Medium-low (10–20k)			−0.090, (−0.240, 0.060), p = 0.240
Medium-high (20–30k)			−0.199, (−0.370,-0.027), p = 0.023
High (> 30k)			−0.165, (−0.357, 0.026), p = 0.091
Vehicle ownership			
No—Reference			
Yes			−0.123, (−0.384, 0.139), p = 0.357
Model fitting-AIC	3013.51	2999.95	2989.95
Model fitting-Log likelihood	−1506.75	−1499.97	−1488.97

Fig. 2. Recreational facilities in Hong Kong.

of two recent reviews, which found positive and strong effects of population density, land use mix, and street intersection density on walking behaviors and overall physical activities for older adults (Barnett et al., 2017; Cerin et al., 2017). These reviews mainly summarized findings from cities with low urban density, much lower than that in Hong Kong, featuring high-density urban development. It is possible that the associations of 3D factors and walking become weaker or insignificant in high-density cities. Recent studies conducted in other high-density cities also find these 3D factors tend to be insignificant (Cerin, Lee, Barnett, Sit, Cheung, Chan et al., 2013; Kamada et al., 2011). The weaker associations of 3D factors and walking in higher urban density are in line with the finding from a multiple-country study, that the odds and frequency of walking may decrease with residential density after a residential density threshold of 12,000 dwellings/km^2. (Christiansen et al., 2016). Further studies are needed to examine the relationship between 3D built environment factors and walking for older adults in cities with different urban density.

5.2. Strengths and limitations

In the current study, we provided not only strong evidence of the urban greenery-walking associations for older adults, but also a new feasible method to objectively assess eye-level street greenery in this research field. Our study used a large sample size to guarantee the reliability and generalizability of the results for the older adult population in Hong Kong. From a methodological perspective, our study is one of the first studies to use GSV and machine learning techniques to assess urban greenery. Recent studies have confirmed that measurements that assess urban greenery using GSV images can be efficient and unique predictors of various physical activity and health outcomes for different age groups (Helbich et al., 2019; Lu, 2018). Recent studies noted the importance and reliability of objective environment measures to understand the relationship between the environment factors and physical activity, but we still need to better understand the perceived measures, as the environment is closely connected with human beings (Foster et al., 2009; Grasser et al., 2013). Our study used an objective approach to measure greenery exposure, combining the advantages of both perceived and objective measurements. The new method may better capture what pedestrian perceive and estimate daily greenery exposure, compared with traditional bird's-eye-perspective metrics developed form remote sensing images or land use cover maps.

This novel method to assess can be used by urban planners, public health professionals and policymakers to objectively and accurately estimate eye-level street greenery at a large scale. These data can inform further public health studies of the impact of street greenery on an array of physical activity and health outcomes. They can also guide urban planners by identify existing areas which need potential greenery interventions.

This study has several limitations. First, the extracted GSV greenery may be underestimated, because greenery could be blocked by vehicles trucks or pedestrians in streetscape images. Second, the seasons in which GSV images were taken may affect the degree of greenery extracted from those images. As our data suggested, there is moderate variation of seasonality among our GSV images; 59.2% of images were taken in winter and the remaining 40.8% were taken in other three seasons. However, seasonal fluctuation of vegetation growth is not severe in Hong Kong because of its subtropical climate and dominant evergreen and semi-evergreen vegetations. In addition, GSV images are updated periodically and cannot indicate real-time greenery. Besides, the health status and employment of participants were not included in the survey, which may also affect the results for this study. Furthermore, the GSV images were sampled every 50 m; the distance may be inappropriate for short street segment. There is a potential spatial mismatch between urban greenery exposure and walking behaviors. The urban greenery exposure was examined within a circular buffer of 800 m around residential location. However, the walking behaviors may occur outside this buffer. Nevertheless, the bias of spatial mismatch may be minor because most walking trips started from or end at home. Last, similar to other cross-sectional studies, this study's results cannot explain any causal effects between street greenery and the walking behavior. More rigorous research design, e.g. natural experiment, are warranted in this field.

6. Conclusion

This study confirmed the positive relationship between street greenery measured by Google Street View images and the walking behavior of older adults in Hong Kong. The findings from our study indicate that street greenery can be an advanced method for assessing residents' daily exposure to urban greenery. To create an ageing-friendly and healthy city, this study suggests that government and urban planners need to develop landscape design strategies from pedestrian and human-scale perspectives.

Note: All codes developed by the authors are available upon reasonable requests.

Declaration of Competing Interest

None.

Acknowledgements

The work described in this paper was fully supported by grants from the National Natural Science Foundation of China (No. 51578474, 51778552, 41871140), the Research Grants Council of the Hong Kong Special Administrative Region, China (No. CityU11666716) and the

Innovative Research and Development Team Introduction Program of Guangdong Province (No. 2017ZT07X355).

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