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Associations between overhead-view and eye-level urban greenness and cycling behaviors

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ABSTRACT

Cycling is one type of physical activities with documented health and environmental benefits. Little consensus has been reached about the impacts of urban greenness on cycling behavior because of the widely varying estimation techniques, especially at street scale. We objectively measured the urban greenness in two ways: overhead-view greenness by Normalized Difference Vegetation Index (NDVI) and eye-level street greenness by Google Street View (GSV) images. Multilevel logistic regression models were used to examine the association between urban greenness and the odds of cycling (versus not cycling) for 5701 Hong Kong participants after controlling activity-influencing built environment and individual-level covariates. We found the odds of cycling were positively associated with eye-level street greenness but not with overhead-view greenness across three buffer zones: 400 m, 800 m and 1600 m. In addition, the odds of cycling were negatively associated with population density, number of bus stops, and terrain slope, while positively associated with bike lane density. To build a cycling-friendly city, planners and designers might need to pay more attention to improve citizens' daily exposure to urban greenness, instead of traditional greenspace indices such as greenspace area or number of parks. The GSV technique is a novel and reliable method for measuring eye-level urban greenness with potential usage in further healthy city studies.

1. Introduction

Maintaining regular physical activity has documented health benefits, such as reducing the risk of type II diabetes, cardiovascular diseases, and some types of cancer, and improving physiological and psychological health (Lee et al., 2012). However, approximately one third of adults worldwide do not the meet the World Health Organization's recommendation of 150 min moderate to vigorous physical activity a week (World Health Organization, 2010). Cycling for recreational or transport purpose can potentially increase moderate to vigorous physical activity levels among children and adults because it is economical and convenient, and it can be incorporated in a person's daily routine (Oja et al., 2011; Rabl & de Nazelle, 2012; World Health Organization, 2010). Besides the health benefits, cycling also has environmental benefits by reducing CO_2 emissions, air pollution, and traffic congestion (Fraser & Lock, 2011; Oja et al., 2011).

Nonetheless, cycling rates in developing countries have dropped sharply during last several decades due to urbanization and rates remain low in developed countries (World Health Organization, 2010). It is quite feasible to increase cycling rates globally because some surveys showed that about half of private vehicle trips were shorter than 5 km, which can be easily replaced by only 15 min cycling trips (Pucher & Buehler, 2008a, 2008b).

Understanding the impact of different characteristics of built environment on cycling behaviors can shed lights on developing urban design and planning policy which can create a cycling-friendly environment and promote cycling and overall physical activity among adults (Kerr et al., 2016; Mertens et al., 2017; Zahabi, Chang, Miranda-Moreno, & Patterson, 2016). Urban greenness is believed to be an essential factor for the participation of cycling, because the urban greenness can make the cycling environment more pleasant and attractive (Chen, Zhou, & Sun, 2017; Christiansen et al., 2016; Xiao, Lu, Guo, & Yuan, 2017). The empirical findings of the urban greenness-cycling associations were inconsistent, partly due to the varying estimation techniques of urban greenness across different studies (James, Banay, Hart, & Laden, 2015; Lachowycz & Jones, 2011). It is worth

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noting that street greenness is often omitted in the previous studies because it is difficult to be objectively assessed. The detailed measure of greenness warrants further improvement, which is the focus of the present study.

2. Literature review

2.1. Built environment and cycling

According to socio-ecological model, cycling behavior is influenced by the multi-level factors including: individual factors (e.g. socio-demographic characteristics and attitude towards cycling), social environment (e.g. socio-economic status of a community, social and policy support), and built environment (e.g. urban density, cycling infrastructure, and urban greenness) (Sallis et al., 2006). Characteristics of built environment are increasingly being recognized as important factors shaping cycling behaviors. Those built environment characteristics can be broadly categorized as accessibility, safety, and aesthetic factors (Chen et al., 2017; Christiansen et al., 2016).

First, Cycling, as a nonmotorized transportation mode, is more affected by trip distance than motorized transportation modes. Previous empirical studies have established that travel distance is an important predictor for bicycling mode choice (Chillon, Molina-Garcia, Castillo, & Queralt, 2016; Handy, Van Wee, & Kroesen, 2014; van Wee, Rietveld, & Meurs, 2006). In China, Yang and Zacharias found relatively short commuting distance for many commuters in Beijing; 47.9% of residents and 32.5% of motorized commuters travel < 5 km in three urban districts (Yang & Zacharias, 2016). Correspondingly, a survey in Shanghai showed that in 80% of trips within 5 km distance, cycling was a time-saving traveling mode compared with other alternatives (Sun & Zacharias, 2017; Zacharias, 2005). Trip distance correlated with several accessibility-related built environment factors: urban density, land-use mix, street connectivity, provision of destinations. A compact and mixed-used urban environment with better street connectivity and closer proximity to destinations, can reduce trip distance and hence promote cycling behaviors (Christiansen et al., 2016; Dill, 2009; Fraser & Lock, 2011).

Second, cyclists typically prefer a safe experience when traversing through the city. The safety-related factors include layout of street network and presence of dedicated cycling lanes or path (Dill, 2009; Heesch, Giles-Corti, & Turrell, 2014; Mertens et al., 2017). A denser street network can reduce driving speeds and reduce the perceived risk for cyclists. The presence of dedicated cycling lanes can separate cycling from other traffic and increased cyclist's safety.

Third, aesthetical factors are essential in encouraging cycling behaviors, besides accessibility and safety related factors. Among aesthetic factors, the presence of urban greenness plays an important role in promoting cycling, because the presence of urban greenness often gives cyclists a more pleasant experience (Cole-Hunter et al., 2015; Fraser & Lock, 2011; Krenn, Oja, & Titze, 2014).

2.2. Urban greenness and cycling

Research has demonstrated the urban greenness with physical activity and health. Living with greener areas was associated with healthy weight outcomes of residents (Sarkar, 2017). However, as an important built environment factor, urban greenness and its effects on cycling remain mixed. In addition, the definition of urban greenness varies across disciplines and research fields, but usually includes trees and vegetation along streets, in public parks, gardens, or other green spaces (Wolch, Byrne, & Newell, 2014). Some studies have found a moderately positive association between urban greenness and cycling behavior (Cole-Hunter et al., 2015; Fraser & Lock, 2011; Kerr et al., 2016; Krenn et al., 2014). For example, researchers report that cyclists preferred longer routes with more greenness over the shortest routes by investigating the actual cycling route choices for 113 participants in Graz, Austria (Krenn et al., 2014). Greenness were motivators for bicycle commuting in Spain, where the researchers found the amount of greenness surrounding the workplaces were significant positive determinants of the willingness of bicycle commuting (Cole-Hunter et al., 2015). A study revealed that the amount of greenness surrounding the work/study places was positively associated with the odds of commuting by cycling for 769 participants in Barcelona, Spain (Cole-Hunter et al., 2015).

Nevertheless, some empirical studies have not observed such an association (Christiansen et al., 2016; Sun, Du, Wang, & Zhuang, 2017), or even reported unexpected negative association (Mertens et al., 2016; Mertens et al., 2017). For example, an international study reports that the presence of trees was associated with shorter transport-related cycling time among those who had cycled in the last week for 3904 participants in five large cities of five European countries (Mertens et al., 2017). Another international study comparing the cycling behavior of participants from 14 cities across 10 countries, finds no significant associations between the number of parks and transport-related cycling, and the association was significantly moderated by the city (Christiansen et al., 2016).

2.3. Measurements of urban greenness

The inconsistency in the evidence of the effects of urban greenness on cycling behavior can be attributed to varying estimate techniques, scales, unit of analysis for urban greenness (James et al., 2015; Lachowycz & Jones, 2011). Exposure to urban greenness can often be assessed either subjectively or objectively. Subjective assessment captures resident's perception of urban greenness, such as quantity and quality, using methods such as questionnaires and interviews. However, subjective assessment of urban greenness is prone to recall bias or social desirability bias (Adams et al., 2005). Objective assessment often calculates the quantity of urban greenness based on land use datasets or satellite imagery and avoids the bias of self-report methods (Sallis et al., 2009). In addition, objective methods can collect data efficiently regarding manpower and cost.

Objective methods for estimating greenness typically include the number of parks, size of green space, tree count within a study area. Emerging satellite imagery techniques provide opportunities to measure overall greenness for a given area. One commonly used indicator is the Normalized Difference Vegetation Index (NDVI) (Rhew, Vander Stoep, Kearney, Smith, & Dunbar, 2011). The NDVI measures the amount of green vegetation from multispectral satellite imagery. Studies have found positive associations between the NDVI measured greenness and health outcomes, including increased walking, lower Body Mass Index, and lower rates of depression, anxiety, and stress symptomology (Almanza, Jerrett, Dunton, Seto, & Pentz, 2012; Orban, Sutcliffe, Dragano, Jockel, & Moebus, 2017; Tilt, Unfried, & Roca, 2007). However, some researchers have argued that the NDVI cannot represent the perceived greenness because it is extracted from an overhead view, not at the eye level (Gascon et al., 2016). In the same vein, some empirical studies showed that the perceived greenness had a stronger association with active-travel behavior than NDVI (Ali, Di Nardo, Harrison, & Verma, 2017; Tilt et al., 2007). For example, NDVI was insignificantly associated with walking behaviors, while self-reported greenness was significantly associated, for 529 participants in Seattle, Washington, US (Tilt et al., 2007).

2.4. The research gaps

Empirical studies about the associations between urban greenness and cycling behaviors have almost exclusively focused on parks rather than street, although street greenery is an important component of cycling environment. The omission is partly because street-scale urban greenness is relatively different to quantify (Chen et al., 2017; Lu, 2018; Lu, Sarkar, Ye, & Xiao, 2017). Street greenness includes many types of

Fig. 1. Remote-sensed imagery technique cannot accurately estimate the perceived greenness by pedestrians or cyclists. For example, they cannot detect (a) vegetation covered by a canopy or (b) green wall.

vegetation, such as trees, lawns, green wall, or shrubs, challenging to be assessed objectively. In addition, most cycling trips occurred in streets or cycling lanes rather than in parks. Thus street greenness may be more relevant to cycling behaviors than overall greenness, such as the NDVI estimation. Furthermore, overhead-view greenness measures may be inaccurate to assess the amount of greenness perceived by a cyclist on streets (Jiang et al., 2017; Li et al., 2015). Remote-sensed imagery, for instance, often fails to detect lawns or shrubs covered by a canopy, or vertical green walls (Fig. 1).

To address this methodological limitation, the present study used Google Street View (GSV) technique to assess street greenness. GSV images provide panoramic streetscape images in many global cities. Those streetscape images were captured by cars or people moving along streets, hence bear a close resemblance to what cyclists see on streets. The amount of street greenness extracted from GSV images, can accurately represent the perceived greenness for cyclists (Li et al., 2015). GSV has been validated as reliable and free data for evaluating general neighborhood environments (Charreire et al., 2014; Rundle, Bader, Richards, Neckerman, & Teitler, 2011), urban greenness (Li et al., 2015), or urban open spaces (Edwards et al., 2013). In a recent study, both the quantity and quality of street greenness assessed by GSV was positively associated them with the recreational physical activity occurring in green outdoor environments of 1390 participants in 24 housing estates in Hong Kong (Lu, 2018). The amount of street greenness assessed by GSV was positively correlated with both the odds of walking and total walking time for 90,445 urban residents in Hong Kong (Lu, Sarkar, & Xiao, 2018). To our knowledge, GSV technique has not been used to study the association between street greenness and cycling behavior yet.

In the present study, we examined the association of street greenness assessed by GSV and cycling behavior for 5701 participants in Hong Kong after adjusting for other built environment and individual factors. For comparison, the overall greenness was assessed with NDVI and included in the statistical models. Based on existing research findings, we hypothesized positive effects of both street greenness and overall greenness on participants' cycling behaviors.

3. Method

3.1. Participants and cycling data

Hong Kong is a densely populated city on the southeast coast of China, with a land area of 1104 km^2. In 2015, its population was 7.29 million, with a gross population density of 6603 people per km^2 (Census & Statistics Department of Hong Kong, 2016). The population density is even higher in built-up areas, comprising only 25% of land area. The remaining 75% of land is preserved for country parks or natural areas.

The cycling behavior data for this study were obtained from the 2011 Hong Kong Travel Characteristics Survey (HKTCS), which was conducted by the Transport Department to study the travel patterns of Hong Kong residents. The HKTCS comprised one main survey and five linked supplemental surveys, one of which focused on cycling behavior. The supplemental cycling survey comprised 5701 residents of 5701 households spatially distributed throughout Hong Kong. The survey households were randomly selected from a list of all permanent dwelling addresses in Hong Kong, maintained by Census and Statistics Department. One household member aged 15 or above randomly selected from each household was interviewed. The survey response rate was 71%. Trained interviewers conducted face-to-face interviews to collect data about the participants' demographic (e.g. age, gender) and household information (e.g. household income, private vehicle ownership). Participants were asked to recall how frequently they cycled in the preceding three months. All dwelling locations were extracted and geocoded in a geographic information system software (ArcGIS 10.5, ESRI, USA).

3.2. Urban greenness

The study measured urban greenness in two distinct ways: street greenness by GSV and overall greenness by NDVI. The NDVI was used to assess gross urban greenness for a whole area from a multispectral imagery dataset, based on the contrast between two bands—the chlorophyll pigment absorptions in the red band and the high reflectivity of plant materials in the near-infrared (NIR) band. The NDVI equation is defined as: $NDVI = (\text{NIR} - \text{Red})/(\text{NIR} + \text{Red})$.

NDVI values range between −1.0 and 1.0, with higher values representing more vegetation greenness (Fig. 2a). The average NDVI value within a buffer zone for a dwelling location was used to measure the overall urban greenness in a neighborhood (Fig. 2a). Three buffer zones commonly used in walking/cycling built environment studies were adopted in this study: 400 m, 800 m, and 1600 m. Using multiple buffer zones can also mitigate the modifiable area unit problem (MAUP), which is a statistical bias in which built environment-cycling associations are influenced by the scale of the aggregation unit (Mazumdar, Rushton, Smith, Zimmerman, & Donham, 2008; Swift, Liu, & Uber, 2014).

Street greenness was assessed using GSV images to estimate the level of greenness perceived by cyclists on streets (Jiang et al., 2017; Li et al., 2015). GSV-generating points were created along all streets at a uniform spacing of 50 m (Fig. 2b). The coordinates of the GSV-generating points were input into a Python script, and four GSV images were downloaded for each point, with a 90° field of view and headings

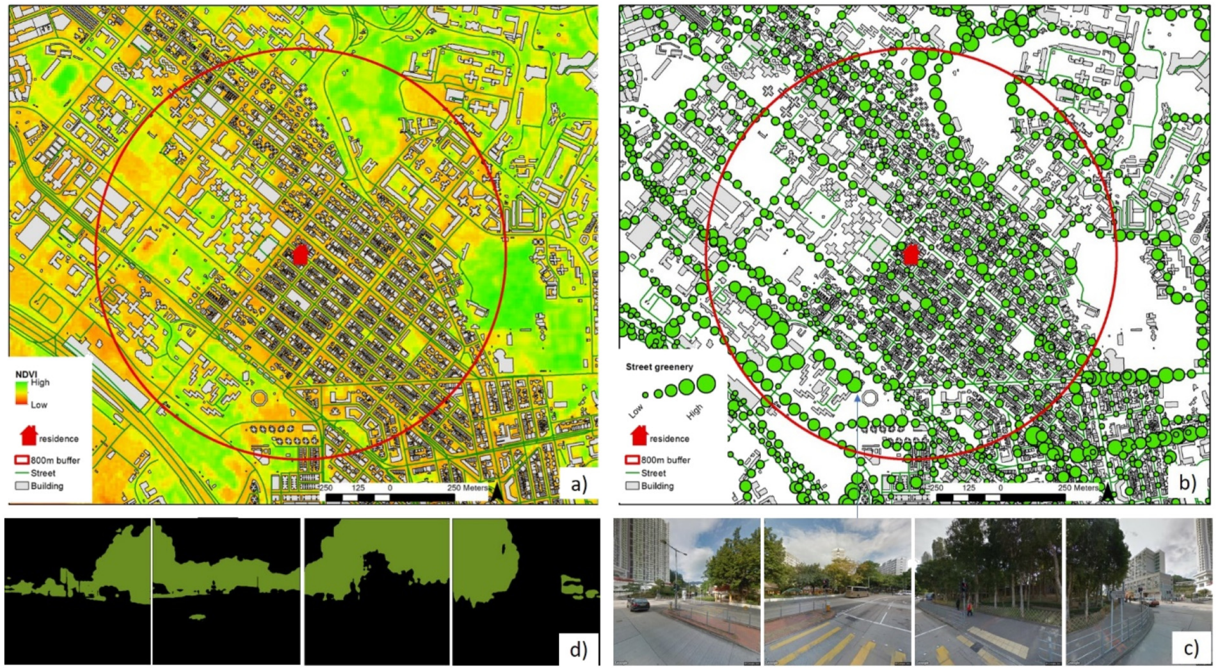

Fig. 2. Overall greenness assessed by NDVI and street greenness assessed by GSV. (a) NDVI of a buffer zone around a dwelling location. (b) Street greenness in the buffer zone around a dwelling location. GSV-generating points were created along all streets with an equal spacing of 50 m. (c) For each GSV-generating point, four GSV images constituting a panorama were obtained with a Python script working with GSV API. (d) The level of greenness at a point location was assessed as the proportion of greenery pixels to total pixels in the four GSV images with deep learning technique.

of north, east, south, and west (Fig. 2c).

A separate script was developed to determine the level of greenness in each GSV image using a deep learning technique of fully convolutional neural network (FCN) (Zhao, Shi, Qi, Wang, & Jia, 2017). This method can accurately identify greenery in images after sufficient training with pre-labelled images (Fig. 2d). The ratio of greenery pixels to total pixels from four images from a GSV-generating point was used to assess the level of street greenness for that point, as shown in the following equation:

$$Street\ greenness = \frac{\sum_{i=1}^{4} Greenery\ pixels_i}{\sum_{i=1}^{4} Total\ pixels_i}$$

The level of street greenness values ranged between 0.0 and 1.0, with higher values representing a high level of street greenness (Fig. 2b). The average value for all GSV-generating points within the buffer zone of a dwelling location was used to assess the level of street greenness in the neighborhood.

The automated vegetation extraction was validated using manual extraction. In our pilot study, 30 GSV images were randomly selected, and their vegetation was manually extracted by a researcher using Adobe Photoshop. The values of the GSV greenness extraction were highly correlated with those of the manual extraction ($r = 0.91$; $p < 0.01$). In line with previous validation studies (Zhao et al., 2017), our results demonstrate that GSV greenness extraction is a reliable method for assessing the level of street greenness.

3.3. Covariates

We calculated activity-influencing built environment factors within three buffer zones in GIS. The factors included population density, street intersection density, land-use mix, cycling lane density, number of bus stops and retail stores, terrain slope, and distance to the closest Mass Transit Rail (MTR) station (Christiansen et al., 2016; Kerr et al., 2016; Winters, Brauer, Setton, & Teschke, 2010). Urban density was assessed by population density, defined as the residential population per unit of land area in participants' neighborhood. Street connectivity was assessed by street intersection density, defined as the number of intersections (three or more streets) per unit of land area. The land-use mix, or entropy score, was calculated by measuring the number of different land use types. Three land use types were considered: residential, retail, and office. A slope raster was interpolated with degree rise as the output from the 10 m contour lines, available from Hong Kong Lands Department. The average slope degree within a buffer zone was calculated based on the slope raster file.

The participants' age, gender, and household income were included as potential confounding factors. The data were extracted from the main survey.

3.4. Data analysis

In the analyses, cycling was measured as a binary outcome (cycling versus not cycling) for 5701 participants, because the frequency of cycling was not normally distributed, with a majority of participants recalling no cycling behaviors. The original 16-band household income was coded into a categorical variable with four levels (low [< 15,000 HKD/month], medium-low [15,000–25,000 HKD/month], medium-high [25,000–50,000 HKD/month], and high [> 50,000 HKD/month]). The participants' age was coded into a categorical variable with four levels (15–17 years, 18–35 years, 35–65 years, and ≥65 years). Percentages and counts were used to describe the individual-level variables. Means and standard deviations were used to describe the continuous built environment variables and urban greenness.

Multilevel logistic regression models were used to explore the independent associations of urban greenness with the odds of cycling after controlling for other activity-influencing built environments and individual-level covariates. Random intercepts in the models were used to account for the clustering in the cycling behaviors of the participants in a neighborhood. Individual participants (level 1) were clustered within street blocks (level 2), census-defined units in Hong Kong. Models 1, 2 and 3 were used for three different buffer sizes respectively: 400 m, 800 m, and 1600 m. All analyses were performed in R statistical

Table 1
Participant characteristics (Hong Kong SAR, China, 2011, N = 5701).

Sociodemographic variable	Count	Percentage	Cycling rate
Gender			
Male	2789	48.9%	5.1%
Female	2912	51.1%	4.1%
Age			
15–17 (years)	160	2.8%	7.5%
18–34	1205	21.1%	4.1%
35–64	3276	57.5%	5.7%
≥65	1060	18.6%	1.0%
Household income			
Low (< 15,000 HKD/month)	2058	36.1%	3.7%
Medium-low (15–25,000)	1510	26.5%	4.5%
Medium-high (25–50,000)	1506	26.4%	5.6%
High (> 50,000)	627	11.0%	5.3%
Vehicle ownership			
No	4863	85.3%	4.2%
Yes	838	14.7%	7.0%
All	5701	100%	4.6%

software using the lme4 package for fitting and analyzing the mixed-effects models. Point estimates (odds ratios and standardized β), their 95% confidence intervals or standardized errors, and p values were reported for all models.

4. Results

The descriptive statistics of the individual variables are shown in Table 1. Only 4.6% of all 5701 participants had cycled at least once during the last three months. There were slightly more female than male participants (51.1% vs 48.9%), the female had lower cycling rate than the male (4.1% vs 5.1%). Adolescents (15–17 years) comprised only 2.8% of all participants but had the highest cycling rate of 7.5% among all age groups. The older adults (≥65 years) comprised 18.6% of all participants and had the lowest cycling rate of 1.0% among all age groups. The low-income group (< 15,000 HKD/month) constituted about one-third of the total participants (36.1%) and had the lowest cycling rate of 3.7% among all income groups. The medium-high-income group (25,000–50,000 HKD/month) comprised 26.4% of the total participant and had the highest cycling rate of 5.6% among all income group. Approximately 14.7% of participants had private vehicles in the households, and they had higher cycling rate than those have no vehicles (7.0% vs 4.2%).

The descriptive statistics of urban greenness and the other built environment variables are shown in Table 2. The average street greenness values assessed by GSV were 0.16, 0.15, and 0.16 for the 400 m, 800 m, and 1600 m buffer zones respectively. The average overall greenness values assessed by NDVI were 0.15, 0.16, and 0.18 for the 400 m, 800 m, and 1600 m buffer zones, respectively. The street greenness and NDVI values were moderately correlated (Pearson correlation r = 0.72, 0.71, 0.66 in 400 m, 800 m and 1600 m buffer zones respectively).

The results of three logistic regression models for predicting the odds ratio of cycling were shown in Table 3. Street greenness was positively associated with odds of cycling in all three buffer zones, odds ratio (95% CI): 1.21 (1.00–1.46) in 400 m buffer, 1.25 (1.04–1.51) in 800 m, and 1.36 (1.11–1.67) in 1600 m. On the contrary, overall greenness measured by NDVI was not significantly associated with cycling in any of three buffer zones.

Among the activity-level built environment variables, bike lane density was positively associated with cycling in all three buffer zones, whereas population density and terrain slope was negatively associated with cycling in all three buffer zones. The number of bus stops was negatively associated with cycling in the 400 m and 800 m buffer zones. Among the individual variables, the female participants were less likely to cycle than the male participants. The younger adults (18–34 years) and older adults (≥65 years) had lower odds of cycling compared with adolescents (15–17 years). Household income and vehicle ownership were not associated with the odds of cycling.

5. Discussion

5.1. Urban greenness and cycling

In the present study, we exploited readily available GSV images and objectively assessed the eye-level street greenness from those images, bearing a close resemblance to what cyclists see on streets. The street greenness was positively associated with the odds of cycling for 5701 participants in Hong Kong while controlling for other built environment and individual covariates. By contrast, overhead-view greenness assessed by NDVI was not associated with the odds of cycling. The propensity of cycling may be more likely affected by eye-level street greenness rather than overhead-view greenness. Two factors are at play when it comes to the stronger impact of street greenness than overall greenness on cycling behavior: different scales and viewpoints.

First, cycling behaviors usually occur on streets or dedicated cycling lanes along streets rather than in open green areas, hence they are more likely affected by street greenness. Previous study supports that cyclists are willing to take a longer but greener route than the shortest route (Kerr et al., 2016). The GSV method exclusively focuses on street greenness while NDVI takes account of all types of greenness in the neighborhoods, e.g. parks, farming fields, country parks. Yet in most green areas of Hong Kong, cycling is prohibited (e.g. in parks due to policy) or discouraged (e.g. country parks due to limited cycling infrastructure or steep slopes). In fact, the street greenness mismatches NDVI values in many areas in Hong Kong, due to different land use and

Table 2
Built environment characteristics by buffers (Hong Kong SAR, China, 2011, N = 5701).

Built environment variable	Buffer = 400 m		Buffer = 800 m		Buffer = 1600 m	
	Mean	SD	Mean	SD	Mean	SD
Greenness						
Street greenness (GSV)	0.16	0.05	0.15	0.04	0.16	0.03
Overall greenness (NDVI)	0.15	0.09	0.16	0.08	0.18	0.07
Built environment						
Population density (ppl/km^2)	44,701	32,404	44,701	32,404	44,701	32,404
Land-use mix (entropy score)	0.53	0.28	0.53	0.28	0.53	0.28
Street intersection density (no./km^2)	73.56	40.82	59.84	30.93	45.06	23.39
No. of retail shops	13.42	10.27	37.28	25.22	97.17	61.89
No. of bus stops	18.60	11.34	56.78	34.24	159.00	99.93
Distance to MTR station (m)	951.27	1145.80	951.27	1145.80	951.27	1145.80
Bike lane density (m/km^2)	1200.10	1971.08	982.91	1508.72	645.12	894.84
Terrain slope (degree)	5.36	4.28	6.37	4.23	7.56	3.84

Table 3
Multilevel logistic regression models for predicting the odds of cycling (Hong Kong SAR, China, 2011, N = 5701).

Model predictor	Model 1 (buffer = 400 m)		Model 2 (buffer = 800 m)		Model 3 (buffer = 1600 m)	
	OR (95% CI)	p-Value	OR (95% CI)	p-Value	OR (95% CI)	p-Value
Urban greenness						
Street greenness (GSV)	1.21 (1.00–1.46)	0.046*	1.25 (1.04–1.51)	< 0.001**	1.36 (1.11–1.67)	< 0.001**
Overall greenness (NDVI)	1.04 (0.88–1.24)	0.585	1.02 (0.75–1.39)	0.882	1.14 (0.85–1.54)	0.379
Built environment						
Population density	0.62 (0.49–0.78)	< 0.001**	0.65 (0.51–0.83)	< 0.001**	0.61 (0.48–0.77)	< 0.001**
Land-use mix	0.96 (0.80–1.16)	0.678	0.88 (0.73–1.07)	0.192	0.83 (0.69–1.00)	0.044
Street intersection density	1.05 (0.68–1.62)	0.832	1.23 (0.65–2.29)	0.527	0.94 (0.31–2.86)	0.917
No. of retail shops	1.05 (0.87–1.27)	0.31	0.98 (0.73–1.32)	0.725	0.95 (0.60–1.50)	0.516
No. of bus stops	0.60 (0.44–0.80)	< 0.001**	0.59 (0.38–0.91)	0.017*	0.50 (0.24–1.04)	0.064
Distance to MTR station	1.04 (0.89–1.20)	0.647	1.08 (0.93–1.25)	0.338	1.14 (0.97–1.33)	0.106
Bike lane density	1.32 (1.15–1.52)	< 0.001**	1.34 (1.11–1.61)	< 0.001**	1.34 (1.08–1.66)	< 0.001**
Terrain slope	0.51 (0.40–0.64)	< 0.001**	0.57 (0.45–0.72)	< 0.001**	0.69 (0.56–0.86)	< 0.001**
Individual factor						
Gender						
Male [reference]						
Female	0.73 (0.56–0.96)	0.024*	0.72 (0.55–0.94)	0.016*	0.72 (0.55–0.94)	0.016*
Age						
15–17 [reference]						
18–34	0.47 (0.23–0.95)	0.035*	0.47 (0.24–0.95)	0.036*	0.46 (0.23–0.93)	0.030*
35–64	0.71 (0.37–1.35)	0.292	0.72 (0.38–1.38)	0.323	0.69 (0.36–1.32)	0.261
≥65	0.14 (0.06–0.33)	< 0.001**	0.13 (0.06–0.32)	< 0.001**	0.13 (0.05–0.31)	< 0.001**
Household income (HKD)						
Low (< 15,000) [reference]						
Medium-low (15–25,000)	0.95 (0.66–1.37)	0.787	0.91 (0.64–1.31)	0.615	0.90 (0.63–1.29)	0.564
Medium-high (25–50,000)	1.17 (0.82–1.67)	0.390	1.13 (0.80–1.60)	0.496	1.12 (0.79–1.59)	0.515
High (> 50,000)	1.16 (0.72–1.88)	0.546	1.09 (0.68–1.75)	0.710	1.12 (0.71–1.79)	0.623
Vehicle ownership						
No [reference]						
Yes	1.31 (0.92–1.86)	0.133	1.17 (0.82–1.66)	0.377	1.14 (0.80–1.63)	0.451

* $p < 0.05$.
** $p < 0.001$.

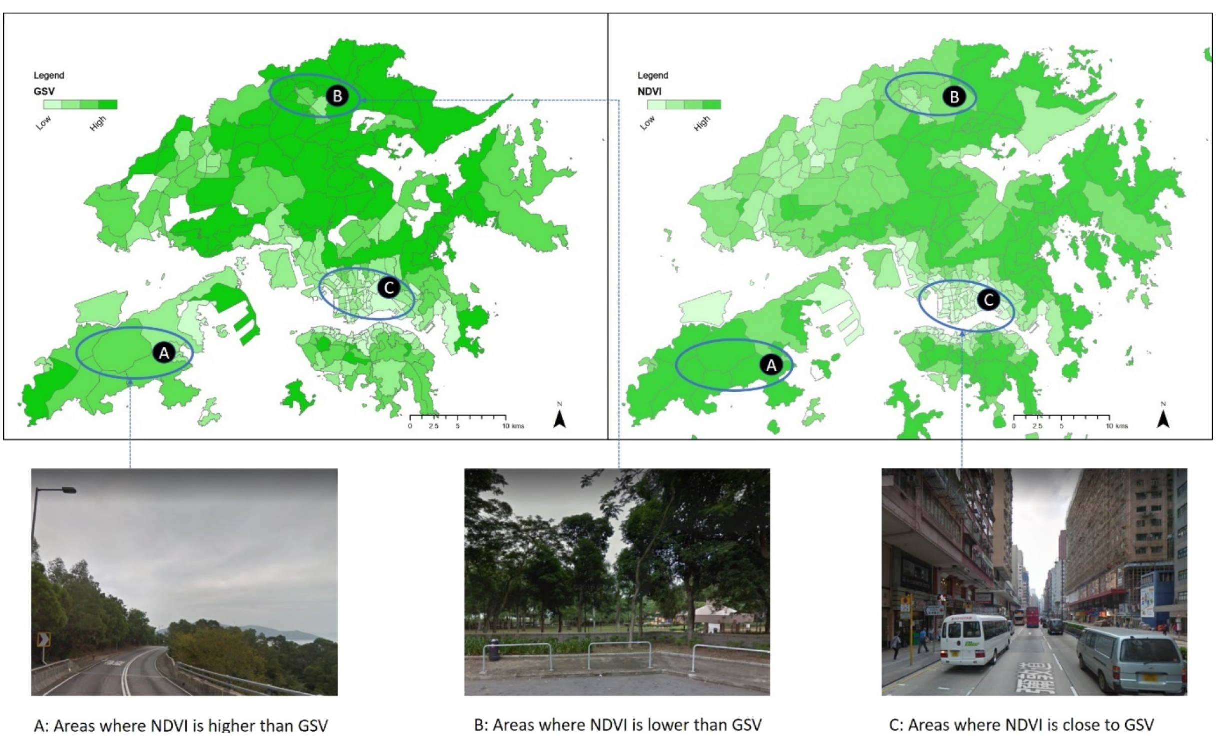

Fig. 3. The eye-level street greenness assessed by GSV mismatches the overhead-view greenness assessed by NDVI in many areas in Hong Kong. (a) NDVI is typically higher than GSV greenness in country parks and preserved areas. (b) NDVI is typically lower than GSV in areas with many brownfields and well-maintained street vegetation, such as new towns in the New Territories. (c) NDVI and GSV are equally low in densely built-up urban areas, such as Hong Kong Island and Kowloon.

urban density (Fig. 3). For example, street greenness is typically lower than NDVI in country parks or other preserved areas; street greenness may be higher than NDVI in new towns in New Territories, where street vegetation is well-maintained and brownfields, former or existing industrial and warehouse sites, are pervasive. Street greenness and NDVI are equally low in dense urban areas, such as Hong Kong Island and Kowloon. The insignificant association of overall greenness found in this study is in accord with the previous finding that the number of parks—another indicator of overall greenness—was not associated with cycling in an international cross-sectional study (Christiansen et al., 2016).

Second, residents see and perceive urban vegetation at eye level, while NDVI measures the availability of urban greenness from an overhead view. Hence, the GSV method more accurately represents the resident's daily exposure of urban greenness than NDVI. Urban residents undertake many trips in daily routines, using bicycles or not. They are constantly exposed to streetscapes while moving through cities. The evidence suggests that the presence of street greenness, such as trees, indeed improves the perceived aesthetics and overall quality of a neighborhood's built environment, which have long been highlighted as crucial predictors of active travel behaviors (Lu, 2018; Saelens & Handy, 2008). For instance, residents give higher aesthetic ratings for urban scenes with more trees (Agyemang et al., 2007; Buhyoff, Gauthier, & Wellman, 1984; Camacho-Cervantes, Schondube, Castillo, & MacGregor-Fors, 2014; Thayer & Atwood, 1978). The street greenness had a positive effect on walking behaviors (Lu et al., 2018). Nevertheless, the overhead-view greenness index, e.g. NDVI, cannot accurately present the amount of greenness perceived by cyclists on streets, especially in locations with high amount of greenness (Jiang et al., 2017; Li et al., 2015). In our study, GSV and NDVI only exhibit moderate correlations ranging from 0.66 to 0.72. The inconsistency between NDVI and perceived urban greenness was documented in active travel behavior studies, although with no focus on cycling (Tilt et al., 2007). For example, subjective greenness but not NDVI was related to the number of walking trips for 529 participants in Seattle, Washington, USA (Tilt et al., 2007). The GSV method may better represent the perceived greenness than NDVI, and hence has a stronger association with cycling behavior.

Our finding of the positive association between street greenness and cycling—as one type of moderate-to-vigorous physical activity—also indirectly supports previous findings of various health benefits of street vegetation in neighborhoods. The presence of street greenness is strongly related to greater longevity for older adults (Takano, Nakamura, & Watanabe, 2002), decreased risks of obesity and asthma in children (Lovasi et al., 2013; Lovasi, Quinn, Neckerman, Perzanowski, & Rundle, 2008), and perceived overall health (De Vries, van Dillen, Groenewegen, & Spreeuwenberg, 2013). It is suggested that street greenness may promote health in three mediating mechanisms: first by providing pleasant setting that promote any forms of physical activity; second by improving air quality and reducing noise; and third by supporting social interaction and forming a sense of community (Hartig, Mitchell, de Vries, & Frumkin, 2014; Markevych et al., 2017). Our finding can shed lights on the understanding of role of physical activity as a mediating effect in greenness-health associations reported in public health studies. Further natural experiment studies including all three variables: greenness, physical activity and health outcomes, are needed to establish causality with confidence.

5.2. Other built environment factors

Besides urban greenness, our study also suggests that several built environment factors are related to cycling behaviors. More specifically, terrain steepness, measured by average slope in an area, is a major barrier for cycling. The propensity of cycling drops in hilly areas, compared with flat areas. The result is in line with previous studies (Ma & Dill, 2015; Winters, Brauer, Setton, & Teschke, 2013; Winters, Teschke, Brauer, & Fuller, 2016). Furthermore, denser bike lanes in the residential neighborhoods contribute to the higher likelihood of cycling. This finding is consistent with previous findings of the significance of provision of cycling lanes and other cycling infrastructure (Buehler & Pucher, 2011; Kerr et al., 2016; Mertens et al., 2017). Several studies reported that cyclists preferred cycling lanes and cycling paths over vehicle roads without dedicated bike lanes (Barnes & Thompson, 2006; Dill, 2009). For instance, a disproportionate share of cycling trips (49%) occurred on streets with cycling lanes or separate cycling paths, comprising only 8% of the city street network (Dill, 2009). Hence, provision of cycling infrastructure, especially in flat land, can be an effective strategy to promote cycling behaviors.

The population density and number of bus stops are negatively related to the odds of cycling, and cyclists avoid dense urban areas in this study. The concern of traffic safety may explain this finding. Areas with more bus stops and residents in Hong Kong are more likely to have heavy vehicle traffic. Other studies also demonstrate traffic safety is negatively associated with cycling behaviors (Kerr et al., 2016; Mertens et al., 2017; Sallis et al., 2013). It is worth noting that urban density also negatively associated with walking behaviors in cities with relatively high urban density (Lu, Xiao, & Ye, 2016; Salvo et al., 2014; Xu et al., 2010). Evidences from western countries often suggest dense urban design can promote cycling and walking (Ding & Gebel, 2012; Durand, Andalib, Dunton, Wolch, & Pentz, 2011). This suggestion, however, may be counterproductive for high-density Asian cities, such as Hong Kong.

5.3. Individual factors

Though our study mainly focused on the relationship between cycling behavior and urban greenness, the results also show some individual factors of cycling behaviors. Regarding gender, our result was consistent with previous research, indicating that males are more likely to ride bicycles than females (Moudon et al., 2005; Rodriguez & Joo, 2004). In term of age, our results show that both younger adults (18–34 years) and older adults (age ≥65 years) have lower odds of cycling compared with adolescents (15–17 years), suggesting a declined propensity of cycling with age (Dill & Voros, 2007; Moudon et al., 2005).

There is positive but insignificant relationship between household income, private vehicle ownership and odds of cycling. The relationship between income and cycling remains unclear in the literature. Some studies reported a positive relationship (Parkin, Wardman, & Page, 2008; Plaut, 2005), while others reported a negative relationship (Dill & Voros, 2007; Stinson & Bhat, 2004). We tentatively suggest that more affluent people in Hong Kong are more likely to be aware of health and have positive beliefs about physical activity, and therefore frequently take part in physical activity such as cycling.

5.4. Implications for urban design and planning

We can draw some important urban planning implications based on the findings. First, cycling is more strongly affected by street greenness rather than overall greenness. To build a cycling-friendly city, planners and designers might need to pay more attention to improve citizens' daily exposure to urban greenness, instead of traditional greenspace indices such as greenspace area or number of parks. Hence to promote cycling behaviors, urban planners should expand their exclusive focus on the provision of large green areas to also consider the permeability and accessibility of those green areas with green cycling corridors (Krenn et al., 2014). By doing the latter, an integrated cycling network can be created by connecting large green areas with other cycling infrastructure. In other words, creating isolated pockets of urban greenness, such as parks, may be inadequate to promote cycling behaviors; a well-connected green cycling infrastructure including cycling lanes, cycling corridor, and parks, is needed. Second, the density of cycling lanes is positively related to cycling behavior. Cycling has also become popular in many high-density cities in China, though most, such as Hong Kong, build isolated cycle lanes only in suburban areas. The lack of a connected cycle lane network in urban areas may prohibit cycling due to traffic safety concerns. Provision of well-connected cycling infrastructure, together with other complementary interventions, such as pro-cycling programs, social support and restriction on vehicle speed may effectively increase cycling use.

5.5. Strengths and limitations

This study has several strengths. It is one of the first studies to assess eye-level street greenness with GSV technology and associate it with cycling behavior in a high-density city. It contributes to the development of more precise measurement of residents' exposure to urban greenness, which public health researchers are long looking for (Hartig et al., 2014). Street greenness assessed with eye-level streetscape images (e.g. GSV) may more accurately represent what a pedestrian or cyclist sees on streets compared with overall greenness assessed with overhead-view land use data or satellite imagery (e.g. number of parks, or NDVI). The GSV assessment can avoid self-report bias associated with the survey. Moreover, the GSV assessment is more efficient in term of time and cost than field audits or survey. The large sample size used in this study also guarantees the generalizability and validity of our findings. The use of multiple buffer sizes demonstrates the robustness of our findings by rule out the modifiable area unit problem (MAUP).

This study also has several limitations. The first is the general low cycling rate (4.6%) in Hong Kong. As a city that heavily relies on the public transportation system, cycling in Hong Kong mostly occurs in the new town, not old urban areas, which may lead to sampling bias. The cross-sectional research design also limits our understanding of the causality between cycling and built environment. For example, engagement in cycling and the provision of cycling lanes affect each other (Dill, 2009). Future natural experiment studies are warranted to determine the causal relationship. Another limitation is that we did not consider the impact of traffic safety and crime in our study, because of the unavailability of such data.

6. Conclusion

This study demonstrates the positive impact of street greenness on the decision to cycle for large population size in Hong Kong. Eye-level street greenness assessed using GSV and deep learning technique has the potential to become a reliable predictor for not only urban greenness but also cycling behaviors, which could contribute to the urban planning and public health research. To build a cycling-friendly and healthy city, planners and designers should pay more attention to improve citizens' daily exposure to urban greenness, instead of traditional greenspace indices such as average greenspace area.

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