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# Association of street greenery and physical activity in older adults: A novel study using pedestrian-centered photographs

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ABSTRACT

Urban parks and tree-lined streets are major components of urban greenspaces, as well as the most frequently used public spaces for senior citizens. Studies have shown significant associations between urban greenspaces and various health outcomes of older adults. However, most of them focused on urban parks or overall vegetation coverage, and few have considered the impact of street greenery. The lack of research attention on the latter is partly because of no method objectively measuring greenery exposure on streets, especially from a pedestrian-centered perspective. In the current study, we recruited 1161 adults aged 60 or above who lived in 12 housing estates in Wuhan, China, and collected their socio-demographic data and 7-day physical activity data. Streetscape photos were taken by trained researchers on sidewalks of all streets in the 800-m buffers from these housing estates. The pedestrian-centered street greenery exposure was extracted from these photos with the machine learning technique of convolutional neural networks along with the pyramid pooling module. Multilevel logistic regression models were conducted to examine the association of the frequency ($\geq$4 days vs. < 4 days) and total duration ($\geq$300 mins vs. < 300 mins) of physical activity with street greenery. Park area, population density, street connectivity, and land use mix within the buffer zone, as well as individual factors, were included as covariates in the models. Results showed that street greenery was positively associated with the odds of achieving 300 mins or more of physical activity per week, but the park area was not. Furthermore, street connectivity and land use mix were positively associated with both the frequency and total time of physical activity. Unexpectedly, population density was negatively associated with the frequency and total time of physical activity. Therefore, adding street greenery or improving existing street greenery can be a vital environment-intervention strategy to create an aging-friendly urban environment.

## 1. Introduction

### 1.1. Global aging and prevalence of physical inactivity

Many global cities are challenged by their aging population. With the advances in healthcare systems and improvements in living standards, lifespan is increasing. Globally, the number of people over 60 years old is expected to double by 2050 (Li et al., 2015; World Health Organization, 2015). China has one of the fastest-aging populations in the world. By 2055, people aged 60 or above will reach a peak of 488 million, which will comprise over 35% of the total population in China (Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, 2019).

This major demographic shift has redirected the research agenda of public health officials, health care providers, and policymakers from extending life expectancy to improving the quality of life and health of older adults. Remaining physically active and healthy are desirable goals for older adults. However, good health in older age is not equally distributed, either between or within countries (World Health Organization, 2016). Most of the health problems of older adults are linked to chronic conditions and particularly noncommunicable diseases (Hegde and Solomon, 2015; Nelson et al., 2007; Soares-Miranda et al., 2016). Many of these diseases can be prevented or delayed by practicing healthy lifestyles, such as regular exercise and eating a healthy diet (Musich et al., 2017). Empirical studies have indicated that even in later years, physical activity has powerful benefits on health and well-being (Hupin et al., 2015; Laurin et al., 2001; Soares-Miranda et al., 2016). As recommended by WHO, older adults should engage in

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at least 150 mins of moderate-intensity physical activity throughout the week, or at least 75 mins of vigorous-intensity aerobic physical activity; to gain additional health benefits, older adults should increase their moderate-intensity physical activity to 300 mins per week (World Health Organization, 2010). However, based on a study conducted in 76 countries, the global prevalence of physical inactivity reaches 21.4% (Dumith et al., 2011), which means approximately one in five adults do not fulfill the WHO's recommendation. The combination of physical inactivity and aging population increases the healthcare burden and decreases the quality of life of older adults. Inadequate levels of physical activity increase the risk of cancer, heart disease, stroke, high blood pressure, and diabetes by 20 %–30% and shorten the lifespan by 3–5 years (Hegde and Solomon, 2015; Nelson et al., 2007; Penedo and Dahn, 2005).

### 1.2. Health benefits of urban greenery for older adults

Urban greenery provides an array of health benefits to urban residents. Recent studies have demonstrated that urban residents living in the neighborhoods with a higher amount of urban greenspaces, comprising parks, landscaped streets, and open greenspaces, tend to have better physical and mental health outcomes, such as reduced long-term stress, a lower risk of chronic diseases, and enhanced health-related quality of life (Coon et al., 2011; Gou et al., 2018; Mitchell and Popham, 2008; Stigsdotter et al., 2010). Additionally, there is strong evidence that urban greenery plays a notable role in promoting physical activity for older adults (Calogiuri and Elliott, 2017). Research suggested that experiencing nature, or exposure to greenery, can encourage older adults to engage in higher levels of physical activity (Calogiuri and Elliott, 2017).

Studies also found that the distance between residences and parks has a significant effect on physical activity. People who live closer to the park are more likely to engage in physical activity and have more time to do exercise (Coombes et al., 2010; Toftager et al., 2011). Another large sample study found the number of available greenspaces in neighborhoods contributed to increased walking and moderately intense physical activity for middle-aged and older adults (Astell-Burt et al., 2014). However, some researchers suggested that park area and distance to the closest park were not significant predictors for physical activity (Kaczynski et al., 2008; Klompmaker et al., 2018). They argued that parks are also places for people to engage in sedentary activities, such as socializing with friends and family, experiencing nature and breathing fresh air (Cohen et al., 2007). Thus, conducting physical activities is not the sole use of parks. Furthermore, parks are not the sole place for people to conduct physical activity. Streets, especially those with greenery, are also suitable places for older adults to conduct physical activity.

### 1.3. Health benefits of street greenery on older adults

Street greenery has been demonstrated to be relevant to public health and physical activity (Astell-Burt et al., 2014; Lovasi et al., 2008, 2013; van Dillen et al., 2012). Compared with other public spaces, physical activity is more likely to occur in neighborhood streets (Giles-Corti and Donovan, 2002; Huston et al., 2003). Thus, physical activity may be associated with street's micro-environment, especially street greenery. Empirical studies have demonstrated that street greenery has a positive association with physical activity (Borst et al., 2008; Sarkar et al., 2015; Sugiyama and Ward Thompson, 2008; Tsai et al., 2019; Vich et al., 2019). A study in Netherlands found that trees along streets are positively related to perceived attractiveness for older adults (Borst et al., 2008). Another study conducted in four Dutch cities found physical activity has stronger associations with the quality of street greenery, compared with the quantity of street greenery (de Vries et al., 2013). Some of the most recent studies have suggested that physical activity mediates the impacts of street greenery on physical health, but the evidence remains insufficient (de Vries et al., 2013; Yang et al., 2020).

### 1.4. Methods of measuring urban greenery

Urban greenery in participants' neighborhoods were often objectively measured in three ways: by park or greenspace assessed from geographic information system (GIS), by overall vegetation coverage assessed from satellite imagery, or by street greenery assessed from street view images (SVIs). Each method has its strengths and limitations. Using the GIS data, the proximity and availability of parks and greenspaces, such as total park area within a neighborhood or distance to the closest park, can be calculated and thus were widely used in previous studies (Kaczynski et al., 2014, 2008; Sugiyama and Ward Thompson, 2008).

Some researchers used remote sensing imagery to assess vegetation coverage in public health studies since 2000, such as the Normalized Difference Vegetation Index (NDVI) (Lovasi et al., 2011; Sarkar et al., 2015). This method can effectively assess overall vegetation level in an area. However, it has several limitations. First, shrubs under the trees, interchanges, or bridges, may be absent from the satellite images, and this may result in a bias of the actual green exposure perceived by pedestrians (Li et al., 2015). Second, the calculation of NDVI or other vegetation index from satellite imagery may be sensitive to several perturbing factors, for example, clouds and soil (Bounoua et al., 2000; Nicholson and Farrar, 1994).

In recent years, SVIs from Google or Baidu have become a novel source to assess eye-level urban greenery. With the recent advances in machine learning techniques, researchers can identify and extract various environmental factors, including the sky, buildings, and greenery from streetscape photos (Li et al., 2015; Liang et al., 2017; Ye et al., 2019). The street greenery index, that is, the proportion of pixels representing vegetation in an eye-level streetscape photo, has been used in several empirical studies related to urban greenery, physical activity, and health outcomes (Lu, 2019; Yang et al., 2019). For example, both the quantity (measured by the street greenery index) and quality of street greenery had a positive association with recreational physical activity in green outdoor environments in a sample of 1390 participants in 24 housing estates in Hong Kong (Lu, 2019). Another study reported that the street greenery index assessed by SVIs was positively associated with both the odds of engaging in walking and total walking time of 10,700 older adults (aged 65 years or above) (Yang et al., 2019).

However, using streetscape photos from Google and Baidu to assess street greenery also has limitations. First, some cities or some areas in a city are not covered in the SVI service. Second, SVIs have been collected and updated infrequently; thus, the available SVIs may not match the planned study period. For example, in a hypothesized study, the physical activity data were collected in the summer of 2019, and the SVIs were captured in the winter of 2018. The level of greenery in winter, as captured in SVIs, would be less than the level of greenery in summer. Hence, the mismatch between SVI and the planned study period could result in errors in the collected data. Third, Google and Baidu collected SVIs from a perspective of a moving vehicle, because SVI-collecting cameras are typically mounted at the top of vehicles. For studies related to physical activity, pedestrians perceive the streetscape from street sidewalks, rather than driving lanes. Therefore, SVIs may not accurately represent the environment and greenery perceived by pedestrians.

### 1.5. Research gaps and current study

To address the aforementioned limitations, we captured eye-level streetscape photos from pedestrian sidewalks to assess the street greenery exposure; such images can be obtained in a short time by trained researchers. Additionally, previous empirical research has mainly focused on Europe and North America, where population density, social context, and lifestyle of their cities markedly differ from

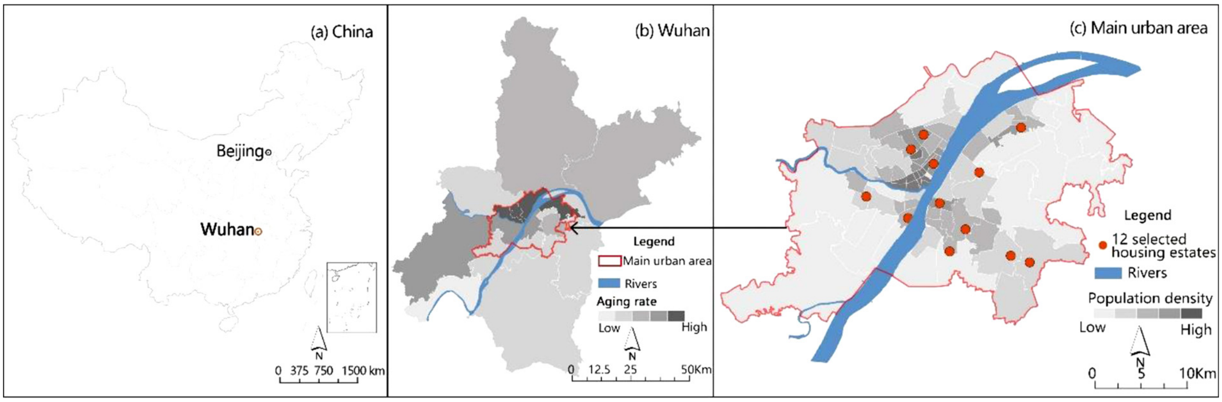


**Fig. 1.** (a) Location of Wuhan in China; (b) proportion of the aging population in different administrative districts of Wuhan; (c) The 12 selected housing estates in Wuhan.

those in high-density cities in China (Astell-Burt et al., 2014; Toftager et al., 2011; Tsai et al., 2019). Findings from our study may provide insights into the impact of street greenery on physical activity in high-density cities.

In this study, we used pedestrian-view photographs to measure the level of street greenery within 12 communities and explored the relationship between street greenery and physical activity of older adults in Wuhan, China. According to our review of the literature, we hypothesized that we would observe a positive association.

## 2. Methods

### 2.1. Sample

Wuhan is a major city in Central China (Fig. 1a). According to the 2018 census data of Wuhan, the proportion of the aging population has been increasing rapidly during the last two decades, and has exceeded 20 % in the main urban areas (Civil Administration Burea of Wuhan, 2019). Seven of the eight administrative districts located in the main urban area have a much higher aging rate than the suburban areas (Fig. 1b). The population density of the main urban area in Wuhan is 5898–25,790 people per km$^2$ (Statistics Department of Hubei Province, 2019), which is much higher than that in Western cities. Based on the aging rate of the main urban areas and the median house price, we selected 12 housing estates in the main urban area as our sample (Fig. 1c).

### 2.2. Physical activity data

This study was conducted from October to November 2019, when there is cool and pleasant weather for outdoor activities in Wuhan. The average temperature was 24℃, while the average humidity is 75 % and the precipitation is 0 (all sunny days). Furthermore, the vegetation is still mostly green during that time. Trained interviewers visited the selected housing estates and interviewed 80–120 older adults by using a convenience sampling method. Trained interviewers walked around public spaces in the housing estates, such as squares and sidewalks, and randomly invited older adults to conduct the interview. All participants were able to engage in physical activity independently and lived in the residence over one year. A total of 1161 valid questionnaires were collected with a 96 % response rate.

The International Physical Activity Questionnaire, Short Form, Chinese version was used to assess physical activity. Because older adults may have difficulty reading or filling the questionnaire, the survey was completed by face-to-face interview and filled by trained interviewers. For this study, the responses to the questions related to the outdoor physical activity were used to measure physical activity level. Outdoor physical activity includes walking for recreation, jogging, riding, dancing, and aerobic exercise. In detail, the following six questions were asked: 1) During the past 7 days, how many days did you walk in the neighborhood for at least 10 mins? 2) Of those days, how much time did you spend walking? 3) During the past 7 days, how many days did you jog or ride in the neighborhood for at least 10 mins? 4) Of those days, how much time did you spend jogging or riding? 5) During the past 7 days, how many days did you do aerobic exercise (e.g., dancing, Tai Chi)? 6) Of those days, how much time did you spend on aerobic exercise? We multiplied the average duration of physical activity time (minutes) and the number of days engaged in physical activity in the past 7 days to obtain the total time of physical activity in older adults.

### 2.3. Street greenery

A participant's neighborhood was defined as a circular buffer zone within 800 m or 10-minute walking distance from the centroid of a participant's housing estate, which are in line with previous studies (Kaczynski et al., 2009; Lu et al., 2018).

All streets in the buffer were sampled to measure street greenery in a neighborhood (Fig. 2a). The street view photographs taken from sidewalks were collected by a mobile app called *Liangbulu (Two-Step)*. This app geocoded all the photographs taken by trained researchers. Trained researchers walked along sidewalks and took four photographs at their eye-level in a uniform spacing of 200 m with headings indicating the front, left, back, and right of the sidewalk (Fig. 2b). The horizontal field of view is 90°; the vertical field of view is 67.5°; the dimension is 4160*3120 pixels in each photo. Furthermore, photos were taken at the height of 1.6 m, approximately at the eye level to mimic what pedestrian can see. The average number of photos of the 12 housing estates was 142.8 (SD = 45.6).

Greenery within the photographs was identified and extracted by the semantic image segmentation of the Pyramid Scene Parsing Network (PSPNet) (Zhao et al., 2017). PSPNet is the machine learning technique based on convolutional neural networks and pyramid pooling module. It can automatically detect all vegetation in a photo, such as trees, shrubs, grass, and flowers (Fig. 3). The reliability of assessing greenery from SVIs using the PSPNet was verified (Lu, 2019). In this study, we performed additional validation test. A researcher manually extracted vegetation in 30 randomly selected photos collected in the current study and compared with that extracted by PSPNet. The accuracy rate of PSPNet was high (Pearson correlation $r = 0.9$, $p < 0.01$).

The Green View Index calculated by the ratio of pixels representing vegetation to total pixels from four images from a photo sampling point was used to assess the level of street greenery for that point, as shown in the following equation:

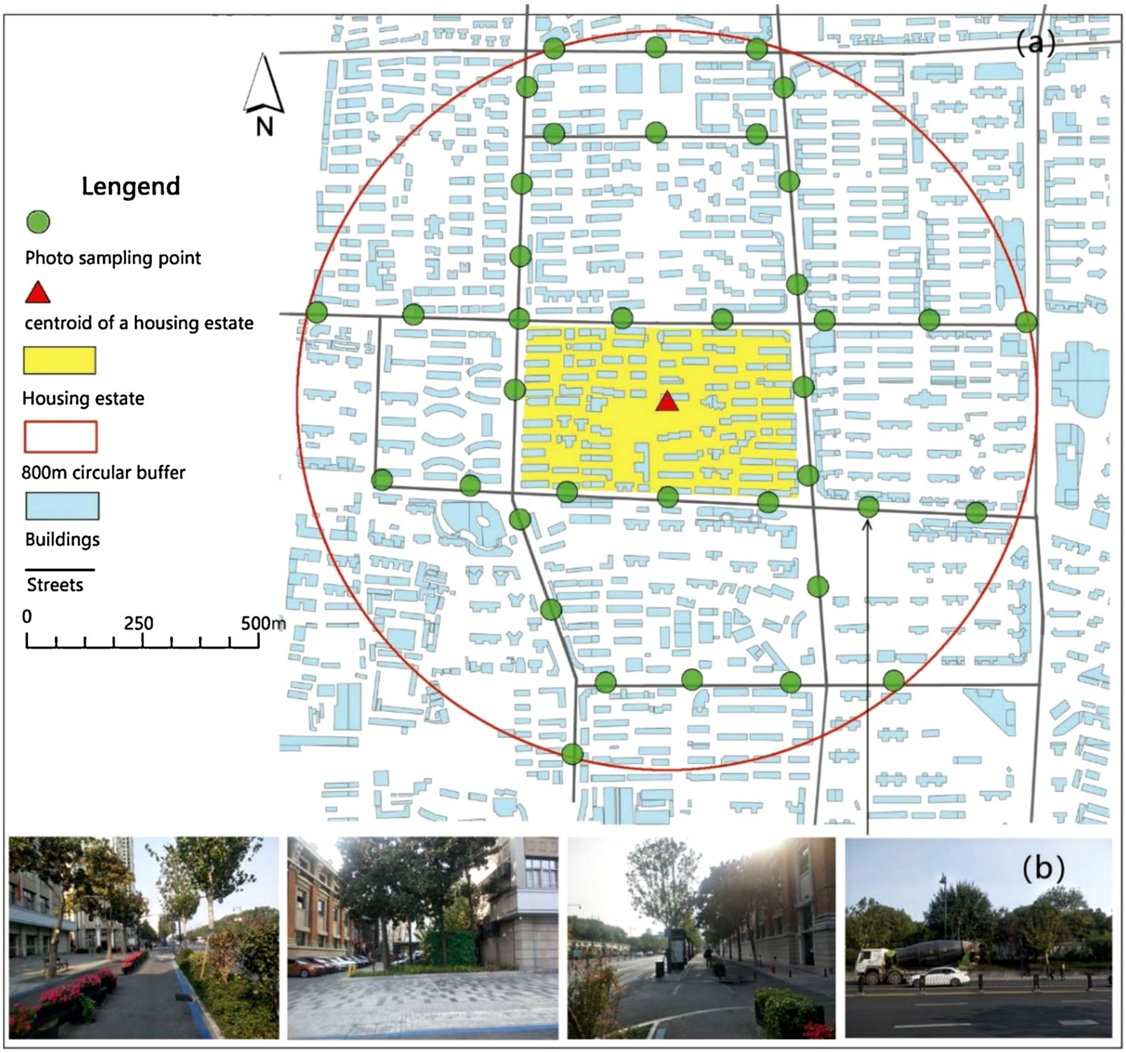


**Fig. 2.** (a) Map of photo sampling point in the buffer area of a housing estate. Grey lines represent the major roads within the 800 m buffer zone, the spacing of each photo sampling point is 200 m. (b) For each photo sampling point, four photographs were taken with the headings of front, left, back, and right, respectively. The photos were taken with the same perspective of a pedestrian.

$$\text{Green View Index} = \frac{\sum_{i=1}^{4} \text{Greenery pixels}_i}{\sum_{i=1}^{4} \text{Total pixels}_i}$$

The average value for all photo sampling points within the buffer was used to assess the neighborhood-level street greenery of a housing estate.

## 2.4. Covariates

We also calculated other physical activity-influencing built environment factors within the buffer zone of 12 housing estates as environment covariates and adjusted them in models. These factors included park area, population density, street connectivity, and land use mix. Park area was calculated by the total area of parks within a

**Fig. 3.** (Left) A street view photograph taken by a trained researcher on a sidewalk; (Right) Street greenery was automatically extracted from the left photograph with a machine learning technique.

neighborhood buffer. Street connectivity was defined as the number of intersections within the buffer zone. We calculated land use mix by measuring the entropy score of different land use types and considered three land use types: residential, retail, and office (Frank et al., 2005).

$$Land\ use\ mix = (-1)\sum_i (p_i \ln(p_i))/\ln(n)$$

Where $p_i$ was the proportion of $i^{th}$ type of land use in total land area, and $n$ is the number of land-use types in a neighborhood.

The participant's gender, age, and education level were also collected as individual covariates. Age was transformed into a categorical variable with three levels, 60–69 years old (reference group), 70–79 years old, and ≥80 years old. The education level was transformed into a categorical variable with four levels: primary school and below (reference group), middle school, high school, and postsecondary school and above.

### 2.5. Analysis

The number of days of physical activity per week was used to measure the frequency of physical activity for older adults. We transformed it into a binary categorical variable (≥4 days/per week vs. < 4 days/per week; the latter was used as the reference group). The total minutes of doing physical activity per week were calculated as the duration of physical activity for older adults. We also transformed it into binary categorical variable (≥300 mins/per week vs. < 300 mins/per week; the latter was used as the reference group). The cutoff value of 300 mins/per week was selected for two reasons. First, the WHO recommends that older adults should increase their moderate-intensity physical activity to 300 mins per week to gain additional health benefits. Second, our pilot study suggested the participants in this study were physically active; approximately half of the older adults performed at least 300 mins of physical activity per week.

For the relationship between street greenery index and physical activity in older adults, a two-step analysis strategy was implemented 1) to examine the association between street greenery index and the odds of doing physical activity four days or more a week (versus doing physical activity less than 4 days) for the 1161 older adults and 2) to examine the association between street greenery and the odds of doing physical activity more than 300 mins per week (versus doing physical activity less than 300 mins per week). Multilevel logistic regression models were used in both analyses. In both analyses, model 1 includes only the street greenery variable and other built environment variables, and model 2 also includes individual covariates.

All analyses were performed in the statistical software SPSS 24.0. Odds ratios (OR), 95 % confidence intervals (CI), and p values were reported for all models.

## 3. Results

Table 1 shows the descriptive statistics of all the participants: 73.47% of the participants engaged in physical activity more than 4 days in the past 7 days, and 52.20% of the participants engaged in physical activity more than 300 mins in the past 7 days. The number of female participants was slightly more than the number of males. The distribution of the age group in our study is consistent with the overall proportion of older adults in Wuhan (Statistics Department of Hubei Province, 2019). Table 2 shows the descriptive statistics of physical activity, street greenery, and built environment characteristics. The multicollinearity among model predictor and covariates were checked with Variance inflation factor (VIF). All VIF values were smaller than 4, indicating multicollinearity were not a problem in our models (Table 2).

The result of the logistic regression model in analysis 1 is presented in Table 3. Street greenery index is not significantly related to the odds of conducting physical activity 4 days or more per week for the older adults after adjusting for covariates. Among other built environment characteristics, street connectivity and land use mix were positively associated with the frequency of physical activity, and population density had a negative association with the frequency of physical activity. We found no significant association between the park area and physical activity. For individual characteristics, participants aged over 80 years old were less likely to conduct physical activity 4 days or more per week than the participants who were 60–69 years old, and neither gender nor education level had a significant association with the frequency of physical activity.

The result of the logistic regression models in analysis 2 is presented in Table 4. Street greenery was positively associated with the odds of engaging in physical activity more than 300 mins per week after adjusting for covariates. Among other built environment characteristics, both street connectivity and land use mix had a positive association with the total time of physical activity, whereas population density was negatively associated with the total time of physical activity. Park area had no significant association with the frequency or the total time of physical activity. For the individual characteristics, participants aged over 80 years old were less likely to conduct physical activity for 300 mins or more a week than the participants who were 60–69 years old. Neither gender nor education level was significantly associated with the odds of engaging in physical activity 300 mins or more per week.

**Table 1**
Descriptive statistics of all participants (N = 1161, Wuhan, China in 2019).

| Individual characteristics | Count | Percentage (%) |
|---|---|---|
| **Gender** | | |
| Male | 539 | 46.43 |
| Female | 622 | 53.57 |
| **Age (years)** | | |
| 60–69 | 545 | 46.94 |
| 70–79 | 416 | 35.83 |
| ≥80 | 200 | 17.23 |
| **Education level** | | |
| Primary school and below | 428 | 36.86 |
| Middle school | 311 | 26.79 |
| High school | 183 | 15.76 |
| Postsecondary school | 239 | 20.59 |
| **physical activity** | | |
| ≥300 mins per week | 606 | 52.20 |
| ≥4 days per week | 853 | 73.47 |

**Table 2**
Descriptive statistics of physical activity, street greenery, and built environment characteristics.

| Variables | MEAN | SD | VIF |
|---|---|---|---|
| Street Greenery Index | 0.21 | 0.05 | 1.606 |
| Park area ($m^2$) | 79015.75 | 67465.61 | 3.023 |
| Population density (#/$km^2$) | 25539.00 | 10868.01 | 2.231 |
| Number of street intersections | 15.00 | 10.69 | 3.079 |
| Land use mix | 0.60 | 0.16 | 1.443 |
| Duration of physical activity (minutes per week) | 337.00 | 249.64 | |
| Frequency of physical activity (days per week) | 5.22 | 2.19 | |

## 4. Discussion

### 4.1. Major findings

This study is one of the first to examine the relationship between physical activity of older adults and street greenery objectively measured by pedestrian-centered photographs in conjunction with a machine learning technique. This novel method can overcome some methodological limitations of using SVIs to assess street greenery. First, our streetscape photos were taken by trained researchers on sidewalks. By comparison, SVIs have typically been taken by data-collecting

**Table 3**
Multilevel logistic regression models for predicting odds of engaging in physical activity 4 days or more per week vs. less than 4 days per week (N = 1161).

| Model Predictor | Model 1 | | | Model 2 | | |
|---|---|---|---|---|---|---|
| | OR | 95 % CI | p-value | OR | 95 % CI | p-value |
| **Built Environment** | | | | | | |
| Street Greenery Index | 1.023 | 0.87 ~ 1.21 | 0.761 | 1.018 | 0.859 ~ 1.206 | 0.838 |
| Park area | 0.957 | 0.76 ~ 1.21 | 0.715 | 0.998 | 0.783 ~ 1.271 | 0.984 |
| Population density | 0.664 | 0.55 ~ 0.81 | 0.000*** | 0.689 | 0.563 ~ 0.844 | 0.000*** |
| Street connectivity | 1.314 | 1.03 ~ 1.676 | 0.028* | 1.298 | 1.014 ~ 1.662 | 0.038* |
| Land use mix | 1.284 | 1.10 ~ 1.499 | 0.002** | 1.288 | 1.099 ~ 1.510 | 0.002** |
| **Individual Characteristics** | | | | | | |
| **Gender** | | | | | | |
| Male (reference group) | | | | | | |
| Female | | | | 0.909 | 0.690 ~ 1.198 | 0.499 |
| **Age (years)** | | | | | | |
| 60–69 (reference group) | | | | | | |
| 70–79 | | | | 1.023 | 0.752 ~ 1.391 | 0.886 |
| ≥80 | | | | 0.654 | 0.448 ~ 0.954 | 0.028* |
| **Education Level** | | | | | | |
| Primary school and below (reference group) | | | | | | |
| Middle school | | | | 0.881 | 0.624 ~ 1.243 | 0.470 |
| High school | | | | 1.455 | 0.931 ~ 2.276 | 0.100 |
| Postsecondary school | | | | 0.894 | 0.620 ~ 1.288 | 0.547 |
| **-2 Log-likelihood** | 1305.456 | | | 1292.989 | | |

Note: * < 0.05 ; ** < 0.01 ; *** < 0.001.

vehicles from Google or Baidu. Hence, our photos may more accurately represent what pedestrians see in their daily lives. Second, our photos were taken in the same time frame as the survey data, whereas the SVIs were outdated because of infrequent updates by Google or Baidu. Therefore, the potential error because of mismatch between street greenery data and survey data was mitigated. Hence, our method may inspire future health studies that focus on the health benefits of street greenery, especially in the situation when SVIs are unavailable or outdated, for example, assessing the greenery on walking paths, cycling lanes, or footbridges.

Findings from our study suggested that the street greenery index of surrounding streets is positively associated with the odds of achieving at least 300 mins of physical activity a week, but park area was not. Our results are inconsistent with the findings that demonstrated that park area may enhance the likelihood of engaging in physical activity (Gong et al., 2014; Kaczynski et al., 2014). Three reasons may explain this difference. First, the older adults in Wuhan generally had a positive attitude toward physical activity. According to our result, more than 70% of participants were engaged in physical activity at least 4 days per week. Second, older adults preferred surrounding streets over parks as their daily activity place because of the safety concern, according to informal interviews. Third, the maintenance and condition of some parks in our study area were mediocre at best. Some parks did not have aging-friendly facilities, for example, public toilets, benches, ramps, and paved sidewalks. The low quality of the parks may reduce park usage and park-based physical activity (Cerin et al., 2013; Ottoni et al., 2016; Parra et al., 2010). Street greenery may stimulate older adults to walk and conduct moderate-intensity physical activity, by making the streets more comfortable and pleasant. Our finding echoes the evidence of several studies (Calogiuri and Elliott, 2017; Lu, 2019; Yang et al., 2019). Thus, providing a pleasant street environment should be a higher priority to enhance the level of physical activity for older adults

**Table 4**
Multilevel logistic regression models for predicting odds of engaging in physical activity 300 min or more per week vs. less than 300 min per week (N = 1161).

| Model Predictor | Model 1 | | | Model 2 | | |
|---|---|---|---|---|---|---|
| | OR | 95 % CI | p-value | OR | 95 % CI | p-value |
| **Built Environment** | | | | | | |
| Street Greenery Index | 1.300 | 1.120 ~ 1.509 | 0.001** | 1.287 | 1.105 ~ 1.498 | 0.001** |
| Park area | 0.896 | 0.731 ~ 1.098 | 0.289 | 0.936 | 0.758 ~ 1.156 | 0.538 |
| Population density | 0.747 | 0.627 ~ 0.891 | 0.001** | 0.769 | 0.641 ~ 0.923 | 0.005** |
| Street connectivity | 1.247 | 1.016 ~ 1.531 | 0.035* | 1.237 | 1.004 ~ 1.524 | 0.045* |
| Land use mix | 1.241 | 1.074 ~ 1.434 | 0.003** | 1.267 | 1.091 ~ 1.470 | 0.002** |
| **Individual Characteristics** | | | | | | |
| **Gender** | | | | | | |
| Male (reference group) | | | | | | |
| Female | | | | 0.827 | 0.646 ~ 1.058 | 0.131 |
| **Age (years)** | | | | | | |
| 60–69 (reference group) | | | | | | |
| 70–79 | | | | 1.066 | 0.812 ~ 1.398 | 0.646 |
| ≥80 | | | | 0.577 | 0.405 ~ 0.821 | 0.002** |
| **Education Level** | | | | | | |
| Primary school and below (reference group) | | | | | | |
| Middle school | | | | 0.792 | 0.581 ~ 1.080 | 0.141 |
| High school | | | | 1.168 | 0.806 ~ 1.691 | 0.412 |
| Postsecondary school | | | | 0.787 | 0.562 ~ 1.101 | 0.162 |
| **-2 Log-likelihood** | 1552.375 | | | 1531.18 | | |

Note: * < 0.05 ; ** < 0.01 ; *** < 0.001.

in Wuhan.

We also found that street connectivity and land use mix are positively associated with both the frequency and total time of physical activity. Our study supports previous findings that land use mix and street connectivity have a positive association with walking and physical activity for older adults (Barnett et al., 2017; Cerin et al., 2017). Neighborhoods with better street connectivity can provide more route choices and more potential destinations, as well as shorter trip distances. Additionally, neighborhoods with better-connected streets may reduce vehicle speed, increasing the perceived safety of older adults. A higher land use mix means that there are more diverse pedestrian destinations within the neighborhoods thus may encourage the likelihood of engaging in outdoor activity for older adults.

Unexpectedly, the finding from our study suggests that population density is negatively associated with the frequency and total time of physical activity, which contrasts with some findings in the literature (De Bourdeaudhuij et al., 2005; Van Dyck et al., 2013). This difference may be explained by the fact that the population density in the other cities was much lower than that in Wuhan. Similar results were found in studies conducted in high-density cities in China, such as Hanzhou (Su et al., 2014) and Nanjing (Xu et al., 2010). Researchers have demonstrated that a high urban density may reduce the size and number of recreational spaces and facilities in urban areas, especially per capita. Additionally, a dense city leads to heavy vehicle traffic and perceived traffic danger among older adults. Thus, older adults' likelihood of engaging in outdoor activity in dense urban areas in China might decrease (Xu et al., 2010). The relationships between physical activity and the built environment may vary in different urban and social contexts; thus, further localized studies are warranted to discover the relationship in detail.

### 4.2. Strengths and limitations

This study was conducted in Wuhan, a high-density city in Central China. Our findings supported some of the findings in the literature, that, the level of street greenery may encourage older adults to engage in physical activity. Our study enriched literature and provides recommendations for urban planners to create a healthy, aging-friendly city in high-density urban contexts.

For the methodology, we used streetscape photos taken from a pedestrian-centered view to extract street greenery and examine its relationship with the physical activity of older adults. Studies have proven that street greenery assessed by Google Street View Imagery can be a reliable predictor for physical activity among adults (Lu, 2019; Yang et al., 2019). We optimized the method by taking streetscape photos on sidewalks during the questionnaire collection period. Therefore, we avoided the potential time mismatch between the SVIs and questionnaire data. Additionally, streetscape photos were taken on sidewalks from a pedestrian perspective, whereas the SVIs were taken from vehicle lanes. Thus many details of sidewalks, such as the pavement, may have been ignored; in comparison, the photos taken in our study may better represent the street environment perceived by pedestrians.

This study also has several limitations. First, as a cross-sectional study, the causal effects between street greenery and physical activity of older adults could not be inferred. Second, an SVI can be obtained online with a large geographic coverage, whereas pedestrian-centered streetscape photos must be collected by trained researchers in the field, which is time-consuming. Third, though we objectively measured street greenery and other built environment characteristics, physical activity data were self-reported with the questionnaire method, which may be prone to recall bias, especially for older adults having cognitive impairment. Further research could use portable accelerometer devices to measure physical activity for older adults. Fourth, because the mobile app used built-in GPS chips to record the location of the photos, there areerrors due to inaccurate or poor signals. Last, we only used park area to measure the availability of parks in current study. The proximity of parks, such as distance to the closest park was not included. Further studies may incorporate more comprehensive measures of parks, to accurately compare the effects of parks and street greenery on health outcomes.

## 5. Conclusion

This study objectively measured the pedestrian-centered street greenery and found it was positively associated with the total time of physical activity among older adults in Wuhan, China. Street greenery, as an indispensable component of urban greenspaces, may play a critical role in promoting older adults' physical activity. Therefore, adding street greenery or improving existing street greenery can be a vital environment-intervention strategy to create aging-friendly urban environments. The new method of assessing street greenery could be used to audit microscale street environment characteristics in further research.

## CRediT authorship contribution statement

**Hui He:** Conceptualization, Supervision. **Xiaowu Lin:** Investigation, Formal analysis, Methodology, Writing - original draft. **Yiyang Yang:** Formal analysis, Writing - original draft, Writing - review & editing. **Yi Lu:** Methodology, Writing - review & editing, Supervision.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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