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Large-scale greenway intervention promotes walking behaviors: A natural experiment in China

Dongsheng He [a,b], Yi Lu [c,d,*], Bo Xie [a,*], Marco Helbich [e]

[a] School of Urban Design, Wuhan University, Wuhan, China
[b] Department of Urban Planning and Design & Urban Analytics and Interventions Research Lab, The University of Hong Kong, Hong Kong Special Administrative Region
[c] Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong Special Administrative Region
[d] City University of Hong Kong Shenzhen Research Institute, Shenzhen, China
[e] Department of Human Geography and Spatial Planning, Utrecht University, Utrecht, Netherlands

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ABSTRACT

Extensive evidence from cross-sectional studies has revealed a positive link between greenspace access and walking behaviors. However, the inherent weaknesses of the cross-sectional research design have provided little causal inference. In this natural experimental study, we assessed the effects of a large-scale greenway intervention (i.e., the opening of East Lake greenway) on walking behaviors in Wuhan, China. Longitudinal survey data on 1,020 participants were collected before and after the intervention in 2016 and 2019, respectively. The results of the mixed-effect difference-in-difference (DID) models showed that the greenway intervention had a significantly positive effect on the walking time, especially for residents living within two kilometers from the greenway. Furthermore, women and socio-economically disadvantaged people benefited most from the greenway implementation regarding walking time. Our findings provided compelling evidence that public investment in transportation infrastructure (e.g., greenway) effectively promotes walking behaviors and mitigates social inequities in physical activity.

1. Introduction

Physical inactivity has gradually become a severe public health issue, one that increases the risk of disease and imposes a significant burden on healthcare systems (Ding et al., 2016). Despite it being well-established that physical activity contributes substantially to physical and mental health (Tessier et al., 2000; Lee et al., 2012; Hegde & Solomon, 2015), average levels of weekly physical activity among adults in China declined by 31% between 1991 and 2011 (Ng et al., 2014). One-third of adults fail to meet the recommended physical activity level (WHO, 2020).

Walking provides a vital opportunity to increase energy expenditure and does not require specific skills or equipment (Hogendorf et al., 2020). Reviews supported by meta-analysis reveal that people's walking behavior is associated with different urban environmental features, including urban density, street connectivity, destination accessibility, and greenspace infrastructure (Ewing & Cervero, 2010; Wang & Zhou, 2017). Whilst predominantly derived from cross-sectional studies (Wang et al., 2021), and susceptible to

* Corresponding authors at: School of Urban Design, Wuhan University, Wuhan, China (B. Xie). Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong Special Administrative Region (Y. Lu).

E-mail addresses: hedsh3@connect.hku.hk (D. He), yilu24@cityu.edu.hk (Y. Lu), xiebo317@whu.edu.cn (B. Xie), m.helbich@uu.nl (M. Helbich).

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methodological limitations, the environmental interventions have been advocated to sustain and improve people's opportunities to walk (Liu et al., 2016). However, the rationale for investing in specific urban infrastructures remains insufficient (Cohen et al., 2013; Craig et al., 2017). To support evidence-based policy-making, more robust research designs are needed to ensure scientific rigor (Craig et al., 2017; Sun et al., 2020).

1.1. Walking and exposure to greenway

Urban greenspaces (e.g., parks, tree-lined streets trees, and greenways) provide safe and attractive places for urban dwellers to participate in healthy activities (Lu et al., 2021; Roux et al., 2007; Yang et al., 2019). Urban greenways are usually considered to be landscaped and traffic-calmed pathways that link parks, open spaces, and public facilities. They are generally planned for multiple purposes (e.g., transportation and recreation) (Horte & Eisenman, 2020), and support a variety of active travel uses (e.g., walking and bicycling) (Ngo, Frank & Bigazzi, 2018; Dallat et al., 2014). Evidence from several cross-sectional studies suggests that creating greenways and making them more accessible are positively associated with walking behaviors (Liu et al., 2016; Astell-Burt et al., 2014).

However, rigorous evidence cannot be established by cross-sectional studies alone because, for example, they are subject to reverse causation and can address self-selection in only a limited way (Yang et al., 2021). This limitation arises because people who have positive attitudes towards walking select to live in greener neighborhoods thus walk more (Guan et al., 2020; Beenackers et al., 2012; Cao, 2015). Consequently, assuming that people intentionally live in their preferred residential environment, the greenway–walking associations cited were probably spurious; that is, observed higher walking levels may have been determined by people's attributes rather than by better access to greenspaces (Gubbels et al., 2016).

1.2. Natural experiments to assess greenway–walking associations

Given the inherent limitations of cross-sectional designs, interest in the use of natural experimental design to better establish causal relationships is growing (Sallis, Story, & Lou, 2009; Veitch et al., 2012; Hirsch et al., 2014). The primary purpose of such designs is to manipulate a treatment variable (e.g., an intervention) and a time variable (e.g., pre- and post-intervention) to determine their causal effect on outcomes (Leatherdale, 2019). Although purely experimental designs (i.e., a randomized controlled trial) are methodologically the most rigorous, they are seldom possible as it is usually impractical for researchers to manipulate an external intervention (e.g., the creation of a greenway) and/or randomly assign people to an experimental group or a control group (Dunning, 2008; Cohen et al., 2013).

An alternative yet robust natural experimental research design was advocated to evaluate the effects of built environment interventions on healthy behaviors (Leatherdale, 2019). In natural experimental studies, the interventions naturally occur, rather than being manipulated by researchers. Such studies typically compare the behavioral changes of nearby residents before and after a greenway creation with those of their counterparts living further away (Hunter et al., 2015). For instance, some studies confirm that the exposed group exhibited significant increases in overall physical activity after a greenspace intervention, relative to the control group (Huston et al., 2003; Frank et al., 2019). Whilst dichotomous measures (exposed vs. unexposed) provided causal evidence, in-depth insights into how changes in residents' behaviors possibly decline with increasing geographic distance from the greenway remain limited (Frank et al., 2019). In response, some studies stressed the need to decode the dose–response function by measuring the residential proximity across multiple distance bands (Xie et al., 2021).

1.3. Greenspaces and social equity

Socio-ecological models capture interdependencies among personal and environmental factors (Gubbels et al., 2016). For example, people with low socio-economic status (SES) may not have sufficient financial means to afford private greenspaces and thus rely more heavily upon the provision of public spaces (Lachowycz & Jones, 2013). However, as shown elsewhere (Wolch, Byrne, & Newell, 2014), greenspaces are generally disproportionately distributed and predominantly benefit affluent neighborhoods (Rigolon et al., 2021). Constrained by safety concerns and a lack of leisure time, women are more sensitive to distance to greenspaces, especially during early motherhood, compared with men (Lee et al., 2001; Bedimo-Rung et al., 2005). Similarly, older low-mobility adults are also sensitive to the distance to a greenspace (Maas et al., 2009). Congruent with environmental justice and social equity literature (Xiao et al., 2017), greenspace should be seen as a public good that is available to everyone, and comprehensive approaches were proposed to address relevant issues.

A series of studies have suggested that creating accessible public greenspaces may combat environmental injustice, especially in deprived neighborhoods (Wolch, Byrne, & Newell, 2014). The logic here was that privately-owned greenspaces were predominantly used by privileged people, and vulnerable groups tended to have limited access to greenspace. Investing in public greenspaces may effectively alleviate the unequal distribution and increase their exposure opportunities to greenspace. Thus, providing accessible, well-maintained, and safe greenspace for vulnerable groups has become a common goal in different countries (Xiao et al., 2017). However, prior observations were limited by their scientific rigor, and longitudinal evidence concerning whether vulnerable groups can get more health and social benefits through greenspace intervention remained unclear (Hunter et al., 2015).

1.4. The contribution of this study

Prior studies on this topic faced the following limitations. First, previous interventions were limited in scale, because the investigated greenway projects were typically within a few kilometers of distance (Frank et al., 2019). Second, most studies used a single distance threshold to define greenway exposure (vs. non-exposure) (West & Shores, 2015). Such a dichotomous measure failed to capture either distance-sensitive effects of greenway interventions on walking or the distance decay of the delivered benefits. Third, these natural experiments predominantly focused upon overall physical activity rather than on walking behaviors (Frank et al., 2019). Overall physical activity levels may not correspond well to domain-specific physical activities (Hogendorf et al., 2020). Fourth, earlier studies paid limited attention to whether the effects of greenway interventions vary across different socio-demographic population strata (e.g., socially disadvantaged groups, older adults) (Gubbels et al., 2016).

To fill these research gaps, our primary goal was to quantify the effects of a large-scale transportation infrastructure (i.e., East Lake greenway) on the walking behaviors of nearby residents by conducting a natural experiment. Our secondary aim was to assess the dose–response effects of such an intervention and determine its catchment area by a novel method to define greenway exposure. Finally, we examined whether the walking-promoting effects of the greenway intervention varied across socio-demographic and socio-economic population strata, in order to ascertain whether the intervention reduced social inequities associated with physical activity.

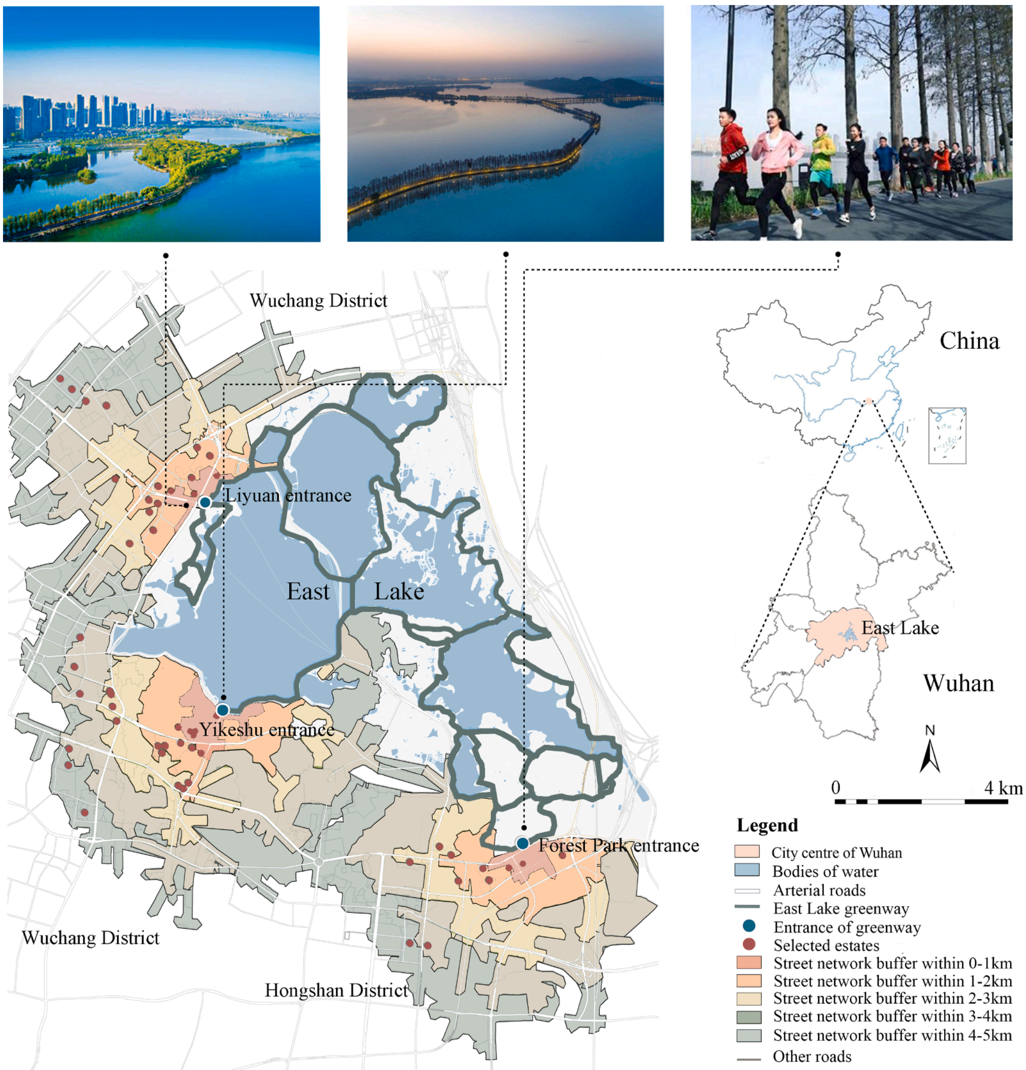

Fig. 1. Study area (East Lake greenway) and sampled housing estates. The pictures were drawn by the authors.

2. Material and method

2.1. Study area

Wuhan has a population of 11.2 million (2019) and is the economic center of Central China (Wuhan Municipal Statistics Bureau, 2020). Due to the presence of numerous bodies of water, Wuhan is also known as the "city of hundreds of lakes". One of these —East Lake, which is located in the metropolitan center—is the largest urban lake in China (Fig. 1).

2.2. The East Lake greenway intervention

The East Lake greenway was developed in 2016–17. The first phase (28.7 km in length) was opened to the public in December 2016, and the remaining part (73.3 km) was opened in December 2017. To improve the urban ecosystem and tourist potential of Wuhan, the local government converted a motorized vehicle road around the East Lake area into a traffic-free greenway with walking trails and biking lanes. Various scenic areas in the greenway (e.g., parks, wetlands, forests, wharves, and historical sites) are connected by multiple routes and paths. Overall, this greenway is significantly longer than other greenway projects that have been investigated (West & Shores, 2011; Frank et al., 2019).

By 2019, the greenway had attracted over 40 million visitors. Owing to these achievements, the greenway was selected as the UN-Habitat's pilot project for improved urban public spaces in China (UN-Habitat, 2016). This high-profile greenway project offers unique opportunities to investigate the impact of large-scale greenspace interventions on walking behaviors.

2.3. Sampling design and surveys

To evaluate the effect of the East Lake greenway on walking behaviors, we conducted a prospective survey in two waves. To capture medium-term behavioral changes, wave 1 took place in 2016 (i.e., before the development of the greenway and wave 2 was implemented three years later. To ensure climatic and seasonal consistency across the waves, both were carried out in April. This procedure ensured suitable apparent temperature and provided desirable weather conditions for outdoor activities. Climatic conditions were similar in both waves. The monthly average temperature at baseline was 21.97 °C (±3.36 °C) with 16 rainy days, and 21.75 °C (±4.51 °C) with 14 rainy days during the follow-up, based on the information of the China Meteorological Administration.

The following three-stage stratified sampling design was implemented at baseline. First, the East Lake greenway has five entrances. Three are located in the urban center (mainly used by local residents) and two are in suburban and scenic areas. Considering that street-network buffers could capture a resident's actual travelling distance to certain facilities, buffers with a width of 5 km were centered on the three urban entrances. In the analysis, both the arterial and sub-arterial roads were contained to reflect objective configuration. This threshold distance was adopted from prior studies on large-scale greenspaces (Merom et al., 2003; Astell-Burt et al., 2016), and Chinese city-level urban greenways are expected to serve residents within a 5 km catchment area (Liu et al., 2016).

Second, created buffers were classified into five segments according to proximity to the greenway (0–1 km, 1–2 km, 2–3 km, 3–4 km, and 4–5 km). In each segment of the buffer, four housing estates were randomly selected. The selection process included equal numbers of low-SES and high-SES housing estates, based on estate-level average housing prices in 2016. However, since households pay a premium to live near the East Lake (Jang & Kang, 2015), high-SES housing estates within a 1 km buffer were inevitably over-sampled. In total, 52 housing estates were randomly selected (Fig. 1).

Finally, we randomly selected people per housing estate based on the total estate population. Considering that residents living close to the greenway tended to be influenced more by this intervention (Frank et al., 2019), participants within 0–1 km and 1–2 km buffers were over-sampled. Face-to-face interviews guided by a questionnaire were manipulated by research assistants. The questionnaire focused upon people's walking behavior, their socio-economic conditions, and demographic characteristics etc. The respondents received a voucher worth 100–200 CNY for completing the survey. More detailed survey information was given in the supplementary materials.

In total, 4,634 respondents were initially approached in wave 1. After removing those with missing or invalid information, 2,331 respondents aged $\geq$ 18 years remained (representing a retention rate of 50.3%). In order to be able to contact them again in wave 2, respondents were asked for their cellphone numbers. After excluding those who were unwilling to participate in wave 2, had relocated by then, or faced data errors (e.g., unreasonably high walking durations), the final valid sample size was 1,020 respondents (retention rate of 43.8%). Ethical approval for the study was obtained from the Research Committee of City University of Hong Kong (No. H000691).

To ensure that our respondents were appropriately representative, we used census data (Wuhan Ststistical Yearbook, 2018) to cross-compare their individual-level characteristics with the overall population of the urban center of Wuhan. The results in Table 1 largely confirmed that there were no differences between our sample and the overall population, except for household annual income

Table 1
Socioeconomic characteristics of the sample and the overall population in the study area.

	Gender (% female)	Average age (in years)	Employed people (%)	Average annual household income (in 1000 CNY)
Sample	56.9	50.8	55.9	202.3
Overall population	51.5	48.6	51.1	143.8

(Xie et al., 2021). This was expected because, as noted, people with high incomes tend to live in the housing estates close to the East Lake.

2.4. Data

2.4.1. Walking as outcome variable

Both survey waves contained identical questions to measure respondents' self-reported walking behaviors. We used the International Physical Activity Questionnaire (IPAQ) (Rzewnicki et al., 2003). The IPAQ has a relatively high validity to assess different aspects of physical activity (Craig et al., 2003). Complementing earlier work on overall physical activity (Xie et al., 2021), we extracted two IPAQ questions to assess walking-related behavior: (1) "How many days have you ever traveled on foot for work, recreation, or exercise purposes for at least 10 min in the past seven days?" and (2) "How long did you, on average, spend on walking per day during the past seven days?" Each respondent's total walking time (in minutes) in the previous seven days was recorded and calculated per wave.

2.4.2. Residential proximity to the greenway as treatment variable

Other natural experiments on greenspace used various distance thresholds ranging from 500 m to several kilometers to distinguish the experimental groups that are exposed or not to an intervention (Frank et al., 2019; West & Shores, 2015). Reasons for various distance thresholds include different types and sizes of intervention implemented in different cultural settings (Frank et al., 2019).

We supposed that the large-scale East Lake greenway attracts people from further away, whereas its benefits decrease with increasing distance from the residential home. Thus, to evaluate the dose–response effects of the greenway, the measurement of residential proximity to the greenway was based on the method mentioned above (see 2.2), and there were five categories representing the proximity levels (0–1, 1–2, 2–3, 3–4, and 4–5 km).

2.4.3. Neighborhood-level environmental covariates

People's neighborhood contexts were assessed within a street-network buffer centered on each housing estate (500 m radius) (N = 52), as undertaken earlier (Su et al., 2013). Based on data obtained from the local planning authority at baseline, the following covariates were computed. Land-use mix was measured through Shannon's diversity index, which represents the heterogeneity in the distribution of seven land-use types (e.g., construction land, residential land) (Xie et al., 2018). A higher value refers to greater land-use diversity. The building coverage ratio was operationalized as the proportion of the area of all the building footprints within the neighborhood (Xia, Yeh, & Zhang, 2020). The number of road intersections was based on the junctions of three or more street segments; a higher level implies a walking-friendly environment. The number of bus stops and parks were based on points of interest (POIs). Given that about 70% of household wealth is invested in the form of real estate property in China (Xie & Jin, 2015), and area-level income data were unavailable, the neighborhood SES was based on the average housing price per housing estate (Moudon et al., 2011). On average, the housing price in the urban center of Wuhan was approximately 20,000 CNY/m^2 in 2016. We therefore used a price of $\geq$20,000 CNY/m^2 in 2016 to identify high-SES neighborhoods; otherwise it was referred to low-SES neighborhoods (Xie et al., 2021).

2.4.4. Individual-level covariates

We controlled for several individual-level demographic and socio-economic covariates. Data were obtained through the survey in wave 1. Age in years was incorporated as a continuous variable, gender was dichotomous (female vs. male), marital status was grouped into married vs. others, employment status was grouped into employed vs. others, educational attainment was grouped into college or above vs. others, and annual household income was included continuously (in 1,000 CNY).

2.5. Statistical analyses

2.5.1. Main analyses

The results of descriptive statistics (i.e., mean and standard deviation (SD)) summarized the characteristics of the valid participants. We used paired *t*-tests to compare changes in the weekly walking time in different groups with unidentical residential proximity across the two waves.

The difference-in-difference (DID) regression model is based on the collective trend of walking time in the control group (assuming non-affected) to simulate the counterfactual scenario of how the trend would have changed in the intervention group (assuming affected), if greenway intervention had not occurred (Wing et al., 2018). Thus we assumed that extended walking-level gaps between two groups were a result of the greenway intervention rather than pre-existing discrepancies in trends (Delaruelle et al., 2019). Due to our hierarchical data structure in which respondents were nested in 52 housing estates, mixed-effect DID models were appropriate with weekly walking time as a response variable. Multicollinearity among the covariates was judged with variance inflation factors (VIF). We report standardized regression coefficients together with their 95% confidence intervals (CIs). Notably, statistical analyses were derived from STATA 15.0.

Model 1 (our base model) included only intervention-related attributes. Given that the intervention condition was not randomly assigned, and individual and neighborhood attributes were different across groups, we iteratively added individual-level covariates (Model 2), and followed with neighborhood-level covariates (Model 3). If the interaction term (e.g., exposure × time) remained statistically significant after covariate adjustment, the non-random assignment would not influence the basic estimation. The fully adjusted Model 3 was:

$$Walking_{ij} = \beta_0 + \beta_1 Proximity_{ij} + \beta_2 Time_{ij} + \beta_3 Proximity_{ij} \times Time_{ij} + \beta_4 Individual_{ij} + \beta_5 Neighbourhood_j + (\varepsilon_{ij} + \mu_j)$$

$Walking_{ij}$ denotes the weekly walking time of participant *i* in neighborhood *j*; β_1 captures the net difference between the participants with different greenway proximity; β_2 captures the change in walking time between the participants in the baseline and the follow-up periods; *Proximity* × *Time* is an interaction term indicating the DID estimate of the effects of the greenway intervention proximity, and β_3 indicates how the effects of the greenway varied by one SD change in proximity to the greenway. $Individual_i$ and $Neighborhood_j$ are vectors of person-level and neighborhood-level covariates, while ε_{ij} and μ_j are individual-level and neighborhood-level error terms, respectively.

2.5.2. Secondary analyses

As secondary analyses, we undertook some stratification to test the heterogeneous response to the impact of the greenway intervention across socio-demographic population strata. Separate DID models were fitted for three socio-demographic strata: gender (male vs. female) (Model 4); SES (low vs. high household income) (Model 5), and age (adults > 60 years vs. group of working age) (Model 6). Considering that changes in walking behavior across the waves could be influenced by changes in the built environment, unmeasured social environment, and lifestyles (Hirsch et al., 2017), a sensitivity test was conducted to ensure that the increment in the weekly walking time was due to actual exposure to the greenway rather than unobserved confounders. To do so, we fitted another DID model to examine the association between weekly exposure time in the greenway and weekly walking time (Model 7).

3. Results

3.1. Descriptive analyses

Table 2 shows descriptive summary statistics. Paired *t*-tests indicate significant differences in the changes in weekly walking time across both waves ($p < 0.001$). The walking time of participants living within 2 km of the greenway increased significantly at follow-up, whereas changes in the walking time of participants living 2–5 km from the greenway are insignificant. For individual characteristics, the attributes of groups with different residential proximity to the greenway show no significant differences, except for educational attainment and SES. Specifically, two groups (0–1 km and 2–3 km) have higher household incomes, and one group (3–4 km) has a lower employment rate. Likewise, participants living 2–3 km from the greenway also have higher education levels.

With respect to the neighborhood environment (Table 3), the different groups are largely similar in terms of the building coverage ratio, land-use pattern, and road intersections. However, neighborhoods located 1–2 km from the greenway tend to have more parks and bus stops, and a higher SES status than the other groups.

3.2. Intervention effect of the greenway on walking behaviors

The VIFs are <2, indicating no issues with multicollinearity. Table 4 summarizes the step-wise DID results. If the interaction term is statistically significant, it suggests that greenway promotes the walking levels of the participants. Specifically, the interaction term in Model 1 is statistically significant, and its coefficient illustrates that the effect of the intervention decreased by 0.048 SD for weekly walking time with a one SD increase in greenway proximity. After adjusting for individual-level (Model 2) and neighborhood-level covariates (Model 3), the effect size of both the interaction terms remain unaffected. Thus, there is a distance decay of the intervention effect. Fig. 2 visualizes the dose–response effects of greenway intervention on walking levels in Model 3, and the estimated coefficient declines with residential proximity.

Table 2
Descriptive statistics of the respondents by residential proximity to the greenway ($N = 1{,}020$).

Residential proximity to the greenway						Overall
	4–5 km Mean (SD)/%	3–4 km Mean (SD)/%	2–3 km Mean (SD)/%	1–2 km Mean (SD)/%	0–1 km Mean (SD)/%	Mean (SD)/%
Walking behaviors						
Weekly walking time at baseline (mins)	451.4 (242.2)	583.8 (241.2)	585.7 (334.1)	535.7 (427.8)	515.5 (385.4)	530.2 (657.5)
Weekly walking time at follow-up (mins)	428.9 (205.1)	582.8 (257.2)	579.0 (334.5)	572.1 (452.2)	566.4 (413.4)	561.4 (399.2)
Changes in weekly walking time (mins)	–22.5 (117.6)	−1.0 (125.02)	−6.7 (190.3)	36.4 (239.1) **	50.9 (203.4) ***	31.2 (206.2) ***
Individual-level characteristics						
Age	54.9 (16.7)	52.3 (14.2)	51.6 (15.3)	51.1 (16.1)	49.4 (16.3)	50.8 (16.0)
Female (Yes = 1)	58.6	62.1	57.7	49.9	60.1	56.6
College or above (Yes = 1)	47.1	48.3	60.8	53.1	46.6	50.3
Employed (Yes = 1)	54.3	41.4	48.5	64.5	54.1	55.9
Married (Yes = 1)	84.3	80.5	81.4	82.4	85.4	83.5
Annual household income (in 1000 CNY)	161.2 (198.3)	134.7 (85.8)	280.8 (599.9)	185.0 (204.2)	218.4 (200.8)	202.3 (263.0)
N (respondents)	70	87	97	335	431	1020

Note: *P*-values were based on pairwise *t*-tests. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Table 3
Descriptive statistics of the neighborhood environment by proximity to the greenway in the baseline survey ($N = 52$).

Residential proximity to the greenway						Overall
	4–5 km Mean (SD)/%	3–4 km Mean (SD)/%	2–3 km Mean (SD)/%	1–2 km Mean (SD)/%	0–1 km Mean (SD)/%	Mean (SD)/%
Building coverage ratio	0.20 (0.03)	0.25 (0.11)	0.21 (0.06)	0.19 (0.04)	0.18 (0.05)	0.19 (0.05)
Land-use mix	1.57 (0.30)	1.38 (0.37)	1.85 (0.24)	1.76 (0.44)	1.64 (0.44)	1.67 (0.42)
Number of road intersections	7.26 (0.42)	5.63 (0.85)	6.02 (1.19)	5.71 (0.96)	7.40 (2.30)	6.55 (1.85)
Number of parks	0.00 (0.00)	0.05 (0.29)	0.03 (0.30)	0.76 (1.10)	0.23 (0.41)	0.36 (0.75)
Number of bus stops	1.34 (1.25)	1.63 (1.33)	2.00 (1.05)	2.63 (1.83)	3.25 (2.61)	2.66 (2.17)
Neighborhood SES (high = 1)	0.46	0.46	0.53	0.45	0.76	0.59
N (neighborhoods)	9	7	8	16	12	52

Table 4
Regression estimates of the effects of greenway intervention on the change in weekly walking time.

	Model 1 Standardized beta (95% CI)	Model 2 Standardized beta (95% CI)	Model 3 Standardized beta (95% CI)
Intervention			
Greenway proximity	−0.007 (−0.09, 0.07)	−0.012 (−0.09, 0.07)	−0.013 (−0.09, 0.07)
Time (post- vs. pre-intervention)	0.158 (0.10, 0.21) ***	0.158 (0.10, 0.21) ***	0.158 (0.10, 0.21) ***
Greenway proximity × time	−0.048 (−0.08, −0.02) ***	−0.048 (−0.08, −0.02) ***	−0.048 (−0.08, −0.02) ***
Individual-level covariates			
Age		0.111 (0.05, 0.17) ***	0.115 (0.06, 0.17) ***
Gender (ref. = male)		0.011 (−0.11, 0.13)	0.009 (−0.11, 0.13)
Education (ref. = high school or below)		−0.131 (−0.26, −0.01) *	−0.150 (−0.28, −0.02) *
Employment (ref. = not employed)		0.078 (−0.05, 0.21)	0.088 (−0.04, 0.22)
Marital status (ref. = not married)		0.033 (−0.12, 0.19)	0.031 (−0.13, 0.19)
Household income		−0.069 (−0.13, −0.01) *	−0.077 (−0.14, −0.02) *
Neighborhood-level covariates			
Building coverage ratio			0.056 (−0.03, 0.14)
Land-use mix			0.052 (−0.05, 0.15)
Number of road intersection			−0.044 (−0.13, 0.04)
Number of parks			−0.007 (−0.11, 0.10)
Number of bus stops			0.054 (−0.04, 0.14)
Neighborhood SES (ref. = low)			0.128 (−0.03, 0.29)
Constant	−0.047 (−0.14, −0.05)	−0.059 (−0.26, 0.14)	−0.127 (−0.35, 0.10)
AIC	4405.72	4393.78	4399.97
N (participants)	1020	1020	1020

Note: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

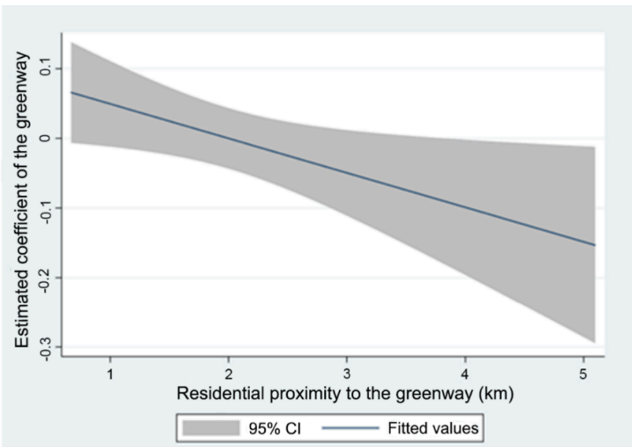

Fig. 2. Dose-response effects of greenway intervention on changes in weekly walking time by residential proximity in Model 3 (variables were standardized).

In terms of the covariates, age is positively associated with the weekly walking time, and higher educational attainment is negatively related to the weekly walking time. Higher income is also inversely associated with the weekly walking time. However, the neighborhood-level covariates (e.g., land-use mix) are statistically insignificant.

3.3. Stratified models

Stratified models for three population strata are fitted to test whether the effects of the greenway intervention reduced social inequity regarding walking level (Table 5). If the significant level of the interaction item is different across the two groups, this means that the effects of the greenway intervention vary among certain groups.

For gender-stratified analyses (Models 4a–4b), the effect of the greenway intervention is significant for females ($\beta = -0.054$; $p < 0.01$), but insignificant for males. For SES-stratified analyses (Models 5a–5b), the influence of the greenway intervention is significant for residents with low SES ($\beta = -0.058$; $p < 0.001$), but insignificant for those with high SES (Model 5b). Results stratified by age show that the relationships between the greenway intervention and weekly walking time are significant for the working-age group ($\beta = -0.055$; $p < 0.01$) (Model 6a), but insignificant for the elderly (Model 6b). These results confirm that the greenway intervention has stronger effects on women and socio-economically disadvantaged people, while it fails to exert more pronounced effects among older adults.

3.4. Robustness analyses

At follow-up, respondents provided their self-reported weekly exposure time to the East Lake greenway after the intervention in 2019. The results in Table 6 indicate that an individual's greenway exposure time is significantly and positively associated with weekly walking time, confirming the robustness of the main analyses.

Table 5
Regression estimates of the effects of greenway intervention on the change in weekly walking time for socio-demographic and socioeconomic strata.

	Model 4a Male	Model 4b Female	Model 5a Participants with low SES	Model 5b Participants with high SES	Model 6a Participants of working age (≤60 years)	Model 6b Older adults (age > 60)
	Standardized beta (95% CI)	Standardized beta (95% CI)	Standardized beta (95% CI)	Standardized beta (95% CI)	Standardized beta (95% CI)	Standardized beta (95% CI)
Intervention						
Greenway proximity	0.021 (−0.07, 0.11)	−0.054 (−0.15, 0.04)	−0.001 (−0.09, 0.09)	0.074 (−0.19, 0.34)	0.007 (−0.09, 0.11)	−0.060 (−0.15, 0.30)
Time period (post- vs. pre-intervention)	0.123 (0.03, 0.21) **	0.185 (0.11, −0.25) ***	0.176 (0.11, 0.24) ***	0.109 (0.02, 0.20) *	0.210 (0.13, 0.029) ***	0.056 (−0.21, 0.03) *
Greenway proximity × time	−0.039 (−0.02, 0.22)	−0.054 (−0.09, −0.02) **	−0.058 (−0.09, −0.02) ***	−0.024 (−0.07, −0.20)	−0.055 (−0.10, −0.01) **	−0.031 (−0.07, 0.01)
Neighborhood covariates						
Building coverage ratio	0.118 (0.02, 0.22) *	0.015 (−0.09, 0.12)	0.036 (−0.06, 0.13)	0.091 (−0.03, 0.21)	0.028 (−0.07, 0.13)	0.132 (0.01, 0.25) *
Land-use mix	0.060 (−0.05, 0.16)	0.018 (−0.10, 0.13)	0.039 (−0.07, 0.15)	0.068 (−0.06, 0.20)	0.090 (−0.03, 0.21)	−0.041 (−0.16, 0.08)
Number of road intersections	−0.099 (−0.19, −0.01) *	−0.050 (−0.16, 0.06)	0.004 (−0.10, 0.09)	−0.300 (−0.46, −0.14) ***	−0.083 (−0.19, 0.03)	−0.028 (−0.13, 0.07)
Number of parks	0.009 (−0.08, 0.10)	−0.025 (−0.14, 0.09)	0.001 (−0.11, 0.11)	−0.035 (−0.20, 0.13)	0.046 (−0.16, 0.07)	0.043 (−0.07, 0.15)
Number of bus stops	0.113 (0.01, 0.22) *	0.007 (−0.12, 0.10)	0.053 (−0.05, 0.16)	0.034 (−0.07, 0.14)	0.024 (−0.08, 0.13)	0.095 (−0.03, 0.22)
Neighborhood SES (ref. = low)	0.234 (0.05, 0.42) *	0.029 (−0.18, 0.23)	0.159 (−0.02, 0.34)	0.068 (−0.19, 0.33)	0.085 (−0.11, 0.28)	0.165 (−0.04, 0.37)
Constant	−0.257 (−0.52, 0.01)	−0.030 (−0.31, 0.25)	−0.087 (−0.34, 0.16)	−0.460 (−0.91, −0.01) *	−0.121 (−0.41, 0.17)	−0.082 (−0.48, 0.32)
AIC	1851.56	2552.41	3610.72	748.08	3002.88	1373.08
Individual-level covariates adjusted	Yes	Yes	Yes	Yes	Yes	Yes
N (participants)	443	577	800	220	655	365

Note: (1) $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.
(2) "Older adults" in this study were adults aged > 60 years.

Table 6
Robustness analyses.

	Model 7 Standardized beta (95% CI)
Greenway proximity	0.015 (−0.07, 0.10)
Time period (post- vs. pre-intervention)	0.174 (0.12, 0.23) ***
Greenway proximity × time	−0.054 (−0.08, −0.02) ***
Weekly exposure time in East Lake greenway	0.126 (0.06, 0.19) ***
Constant	−0.139 (−0.37, 0.09)
AIC	4330.21
Individual-level covariate adjusted	Yes
Neighborhood covariates adjusted	Yes

Note: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

4. Discussion

4.1. Key findings and their interpretation

Numerous cities in China have recently developed different types of public greenspace to support healthy urban living (Liu et al., 2016), but few studies have examined the actual health benefits originating from such interventions. To provide rigorous evidence on walking behaviors, we selected a typical greenway intervention project in Wuhan, China.

Our analysis led to three main findings. First, our results showed that the greenway intervention significantly increased people's weekly walking time, which is consistent with findings from developed countries (Hirsch et al., 2017; Frank et al., 2019). Because urban dwellers in high-density environments tend to have low access to greenspaces due to limited land supply (Lindal & Hartig, 2015), the creation of a traffic-free greenway encouraged residents to participate in physical activity. In addition, numerous developing countries are faced with the challenges of rapid urbanization and the prevalence of sedentary lifestyles, and urban policy-makers should, therefore, pay more attention to optimizing the walkability of routes and paths when creating new transportation facilities (e.g., greenways). The transformation from a motorized vehicle road into a human-oriented transportation infrastructure in Wuhan recommended a valuable practice to other countries.

Second, our analyses suggested a dose–response effect of the greenway and identified its catchment area. Most studies operationalized proximity only as a dichotomous factor, leading to incomplete and inconclusive results that are difficult to implement for spatially targeted policies (Hunter et al., 2015). Our results showed that the walking benefits conferred by the greenway could be extended to residents living within 2 km of the greenway entrances. Possibly due to differences in scale, the attractiveness of the landscape, and the location, the catchment areas of the greenway were larger than in Western settings, where the positive effects were limited to, for example, only several hundred meters (Frank et al., 2019). Considering the large catchment area and high population density (approximately 30,000 persons per km^2 around the East Lake), the population-level walking benefits delivered by the greenway are substantial.

Third, consonant with a review on greenspace and health equity (Rigolon et al., 2021), our results revealed heterogeneous effects conducive to walking of greenspace across population subgroups, as female and low-SES residents experienced the greatest increase in their walking times. This could mean that women are more reliant upon safe and accessible greenways to engage in different walking activities than men, and low-SES residents need public greenspaces because they typically cannot afford private greenspaces (e.g., gardens) (Lachowycz & Jones, 2013). Throughout the planning process of the East Lake greenway, the supply of land, the location of entrances, and accessibility from different types of housing estate were carefully considered (Xie et al., 2021). As our results demonstrate, the benefits of this greenway intervention are more pronounced for socially disadvantaged groups, hence the intervention provides social benefits. Surprisingly, the weekly walking time of older adults (age > 60) was not significantly increased by development of the greenway. This may be attributable to older adults already having a long weekly walking time at baseline and/or having experienced gradual physical deterioration, thus they walked less at follow-up. Considering that unequal access to public greenspaces for different groups has become widespread, interventions should pay attention to both safety and maintenance, while ensuring residential proximity for socially disadvantaged groups.

4.2. Strength and limitations

This study has several strengths. First, it reinforced the argument that greenway intervention is a promising way to promote walking, by providing rigorous evidence using a natural experiment. Second, apart from providing causal inference, it detected the effects of greenway intervention in fine-grained detail, including both the distance-based dose–response effect and the distinctive responses of subgroups. Therefore, the effects of greenway intervention on walking behaviors were depicted in a deeper and more robust way.

A few limitations must be acknowledged. First, the walking data were self-reported, thus prone to recall bias or social desirability bias (Frank et al., 2019). Future studies should collect objective walking data using portable accelerometers and global positioning systems (Birenboim et al., 2021). Second, whilst the effects of natural and built environments on walking probably differ by walking purpose (Saelens & Handy, 2008), we failed to distinguish between recreational walking and transportation walking due to a lack of data, which may have different associations with built-environment interventions (Hogendorf et al., 2020). Third, we only incorporated the built environment at baseline. We cannot overlook that built environment changes in the vicinity of the East Lake greenway have also affected walking behaviors. However, since the two survey waves were only three years apart, we believe that built environment changes were negligible. Fourth, changes in unmeasured socio-environmental features may have had synergistic or supplementary effects on walking behaviors (Hirsch et al., 2017). Finally, the retention rate was relatively low in our study, which may have biased our analyses.

4.3. Future implications

Based on our study, we provide some methodological recommendations for future research. As highlighted in prior studies (Hunter et al., 2016), the rigor of the research design needs to be improved by careful selection of sample size and control group, and well-planned implementation of the follow-up survey. For instance, it is necessary to conduct the follow-up during the same month as the baseline, with sufficient exposure time after the intervention. Meanwhile, evaluations should target populations living in nearby neighborhoods, not only green space users, and ensure the representativeness of the sampled participants. Apart from demonstrating the causal effects of environmental interventions, future studies are advised to account for the concept of 'geography of influence' and investigate the catchment area of infrastructure (Frank et al., 2019), which is essential for operation and further modification.

5. Conclusion

Our robust findings based on mixed-effect difference-in-difference regressions showed that the greenway intervention (i.e., the opening of East Lake greenway in Wuhan, China) increased the weekly walking time of nearby residents, and the catchment area extended to two kilometers from the intervention. Furthermore, the walking-promoting effects of the intervention were more pronounced among women and socio-economically disadvantaged people.

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Ethics approval

Ethical approval for the study was obtained prior to this study from the Research Committee of City University of Hong Kong (No. H000691). All participants provided written informed consent.

CRediT authorship contribution statement

Dongsheng He: Methodology, Formal analysis, Visualization, Writing – original draft. **Yi Lu:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Bo Xie:** Conceptualization, Data curation, Methodology, Supervision, Writing – review & editing. **Marco Helbich:** Writing – review & editing.

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.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2021.103095.

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