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Towards a cycling-friendly city: An updated review of the associations between built environment and cycling behaviors (2007–2017)

Yiyang Yang[a], Xueying Wu[b], Peiling Zhou[b,**], Zhonghua Gou[c], Yi Lu[a,d,*]

[a] Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong, China
[b] School of Architecture, Harbin Institute of Technology, Shenzhen, China
[c] School of Engineering and Built Environment, Griffith University, Australia
[d] City University of Hong Kong Shenzhen Research Institute, Shenzhen, China

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ABSTRACT

Introduction: Cycling behavior has recently attracted great research attention as an important type of physical activity and sustainable mode of transportation. In addition, cycling provides other environmental benefits, such as reducing air pollution and traffic congestion. Various built environment factors have been demonstrated to be associated with the popularity of cycling behaviors. However, the most recent built environment cycling reviews were conducted nearly 10 years ago, and these reviews reached no clear consensus on which built environment factors are associated with which domain of cycling behaviors. To determine the crucial features of a cycling-friendly city, it is therefore necessary to conduct a review based on empirical studies from the last decade (2007–2017).
Methods: Thirty-nine empirical studies published in peer-reviewed journals between 2007 and 2017 were retrieved and reviewed. The results were summarized based on built environment factors and four domains of cycling behaviors (transport, commuting, recreation, and general). Weighted elasticity values for built environment factors were calculated to estimate effect sizes.
Results: We found consistent associations with large effect sizes between street connectivity and cycling for commuting and transport. The presence of cycling paths and facilities was found to be positively associated with both commuting cycling and general cycling. However, the effects of land-use mix, availability of cycling paths to non-residential destinations, and terrain slope on cycling behaviors remained weak. The effects of urban density and other built environment factors are mixed.
Conclusions: This review has demonstrated that street connectivity and the presence of cycling paths and facilities are the two most significant built environment factors that may promote cycling behaviors. With the emergence of advanced measurement methods for both the built environment and cycling behaviors, further studies may overcome current research limitations and provide robust evidence to support urban planning and public-health practice.

* Corresponding author. Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong, China.
** Corresponding author.
E-mail addresses: yiyayang-c@cityu.edu.hk (Y. Yang), 954605706@qq.com (X. Wu), lindaplzhou@gmail.com (P. Zhou), z.gou@griffith.edu.au (Z. Gou), yilu24@cityu.edu.hk (Y. Lu).

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1. Introduction

This review focuses on the impact of built environment factors on cycling behavior, an important form of physical activity. Physical activity has a long-term effect on health and is thus considered by the World Health Organization one of the top five interventions to reduce the prevalence of noncommunicable diseases (Beaglehole et al., 2011). Previous studies have found that walking and cycling for transportation purposes can provide substantial net health benefits, after considering the risks of traffic incidents and air pollution exposure (Mueller et al., 2015). Strong evidence demonstrates that cycling behaviors can reduce the risks of premature death, obesity, heart disease, stroke, type II diabetes, metabolic syndrome, colon cancer and breast cancer among adults (Oja et al., 2011; Pucher et al., 2010a,b; Rojas-Rueda et al., 2011; Rojas-Rueda et al., 2013).

Apart from the common health benefits of physical activity in general, cycling behaviors can provide additional health benefits. Cycling particularly enhances cardiorespiratory and metabolic functions (Gotschi et al., 2016; Haennel and Lemire, 2002). For children and adolescents, cycling can effectively improve cardiorespiratory endurance, muscular fitness, bone health, and cardiovascular and metabolic health (Davison et al., 2008; Voss and Sandercock, 2010). For older adults, cycling can prevent falls, reduce depression, and enhance cognitive functions (James et al., 2013; Rissel and Watkins, 2014).

Furthermore, cycling behaviors provide opportunities to habitually accumulate other types of physical activity, by encouraging people to engage in other forms of moderate to vigorous physical activity (MVPA) more frequently and for longer times (Kerr et al., 2016). In addition to its minimal use of fossil fuels and moderate speed, cycling can also be regarded as a sustainable transportation mode that helps to reduce the use of private vehicles and thus mitigates traffic congestion and improves air quality (Li et al., 2011).

Given the health and environmental benefits of cycling, researchers and policymakers seek to understand why bicycle use differs by location and what built-environment interventions can be implemented to increase cycling levels. Previous studies of the associations between built environments and cycling have demonstrated that several built environment factors are related to different domains of cycling behaviors (Day, 2016; Ferdinand et al., 2012; Fraser and Lock, 2011; Heinen et al., 2010; Saelens and Handy, 2008; Wang et al., 2016). Cycling for transportation purposes was shown to be positively associated with the presence of dedicated cycle routes or paths, the separation of cycle tracks from other vehicle paths, high urban density, short travel distances, and the proximity to green space (Fraser and Lock, 2011; Heinen et al., 2010; Saelens et al., 2003a,b). The environmental factors negatively associated with cycling for transportation include perceived and objective danger from traffic, long travel distances, steep inclines, and the absence of cycle paths (Fraser and Lock, 2011; Heinen et al., 2010). Reviewers demonstrated that shorter distances and a greater land use mix had a positive association with the proportion of people cycling for commuting, while the evidence of possible effects of street connectivity, urban density, the perception of traffic-calming facilities and cycling infrastructure on transportation cycling were mixed (Heinen et al., 2010). For reviews that did not differentiate the domains of cycling, diversely functional and accessible bicycle parking facilities have been found to increase the likelihood of engagement in cycling behaviors (Heinen et al., 2010; Wang et al., 2016).

Recently, researchers have debated whether a highly walkable built environment also promotes cycling behaviors, or in other words, whether walkability equates to bikeability (Muhs and Clifton, 2016). Some researchers have proposed that certain built environment factors, e.g. high urban density, short distance to non-residential destinations, and mixed land use, may promote both walking and cycling behaviors (Saelens et al., 2003a,b; Wang et al., 2016), while others concluded that walking and cycling have different associations with built environment characteristics. For example, cycling behaviors were significantly affected by the presence of cycling infrastructure, such as cycling paths/lanes, and parking facilities, while walking behaviors were not (Buehler and Pucher, 2011).

Existing reviews of built environment-cycling associations have a few limitations. First, most of the reviews tended to focus on cycling for transportation purposes. Second, those reviews were conducted nearly 10 years ago (Fraser and Lock, 2011; Heinen et al., 2010; Pucher et al., 2010a,b). Third, the effect sizes for different built environment factors were not estimated. Hence, it is difficult to predict the effectiveness of any planning interventions. Fourth, none of these reviews included any evidence from developing countries, despite the prevalence of cycling as a major transportation mode in such countries. In China, for example, several large public bicycle-sharing programs, e.g. Mobike, provide an affordable and convenient means of shared transportation for short trips. Since the launch of such programs in 2015, the use of bicycles in China has surged, with nearly 19 million Chinese people now using cycling for their first-mile and last-mile trips (Tsing Hua University Planning and Design Institution and Mobike, 2017). Hence, it is vital to summarize the evidence from recent studies of built environment-cycling associations, as these studies cover a broader scope of geographical locations with different social and urban contexts.

In this review, we performed a meta-analysis to estimate the effects of individual built environment factors of relatively small magnitude on cycling, which are difficult to identify in any single study. Meta-analyses can synthesize outcomes from different studies, and calculate and compare the effect sizes across a range of outcomes in different contexts and sample sizes (Borenstein et al., 2009). For example, Ewing and Cervero (Ewing and Cervero, 2010) conducted a meta-analysis of more than 50 studies on associations between built environment and travel behaviors, with the aim of quantifying the effect sizes and updating earlier related work.

Meta-analyses are useful but also controversial; some limitations are that the results of weaker studies may contaminate those of stronger ones if the results of such different-strength studies are combined, and that choosing published articles may lead to publication bias, given that results with statistical significance are more likely to be published (Rothstein et al., 2005). Despite these caveats, well-designed meta-analyses can effectively summarize existing evidence and guide future research, hence these are widely used in public health and planning fields (Bartholomew and Ewing, 2009; Cerin et al., 2017; Sharmin and Kamruzzaman, 2017).

In sum, we reviewed studies on the associations between the built environment and cycling behaviors conducted between 2007 and 2017. We also estimated the effect sizes of those built environment factors based on elasticity values. Finally, we summarized the evidence and discussed potential directions for future research.

2. Method

The data analysis method closely followed that used in Saelens and Handy's review (Saelens and Handy, 2008). These researchers identified 13 studies published between 2002 and 2006 and another 29 between 2005 and 2006 that focused on the link between walking and the built environment. Day's subsequent review of the correlation between the built environment and physical activity confirmed the replicability and reliability of the method used by Saelens and Handy (Day, 2016). However, Saelens and Handy focused on walking in developed countries and Day focused on physical activity in China, this review focuses on built environment-cycling studies in both developed and developing countries published between 2007 and 2017.

2.1. Search terms and criteria

The terms entered into the Web of Science search engine comprised one term from “cycling,” “bicycle,” “bicycling,” “bike,” “bike use,” and one term from “built environment,” “physical environment,” “urban form,” “urban”. The search field was limited to articles published in peer-reviewed journals in any country and for any population group between 2007 and 2017.

We screened the abstracts of 852 articles in the database and removed those that failed to meet all four criteria below. In the end, our review database consisted of 39 full-text articles, comprising studies which:

1) measured cycling as an individual transport mode or physical activity—instead of being integrated with other modes, such as walking;
2) examined the association between cycling and certain aspects of objective and/or perceived built environment;
3) were published as a research paper in a peer-reviewed journal between 2007 and 2017;
4) were written in English.

The workflow of literature review was shown in Fig. 1 (see Fig. 1). Studies that only addressed the impact of social, cultural, and economic factors, such as household incomes, and personal attitudes, were excluded. In studies examining multiple factors, the results for socio-economic and cultural factors were not considered. The built environment factors were urban design, land use, and transportation system, which are much broader than the scope of physical environment (Handy et al., 2002). Studies that examined only the physical environment were also considered in our review database.

2.2. Review scheme

We followed Saelens and Handy's (2008) approach and selected our review scheme from the first 10 papers. The initial aspects we selected to review comprised the sample size, the data source of the built environment, the factors of the built environment examined, and the units of geographical analysis. After these 10 papers had been reviewed, the research scheme was revised for optimization. Four new query aspects were added: study country, domains of cycling, control variables, and whether self-selection was considered. All the papers were reviewed again according to the new optimized research scheme, and the findings were summarized and presented in a detailed table (see Table A.1).

2.3. Summary tables

Table A.1 lists the following information from each paper: study country, sample, source of built environment data, built environmental factors, geographical analyzing units, cycling metrics, controlled variables, whether self-selection was controlled, and results. The term “cycling metrics” refers to the attributes of cycling behavior, such as duration, frequency, choice of route, and proportion of the cycling population. Self-selection refers to the tendency of people to choose their neighborhood of residence based on their travel abilities, needs and preferences (Naess, 2009). Hence, the associations observed between built environment and cycling may be explained by personal attitudes and preferences, rather than a true impact of built environment on cycling. Studies usually attempted to control for residential self-selection, and confounding factors included attitude variables (AT), socioeconomic variables (SE), weather variables (WE), level of service variables (LE), station variables (ST), and other variables (OT), which referred to the categories and approaches listed in a review conducted by Cao and Mokhtarian (Cao et al., 2009).

Table A.2 elaborates on the details provided in Table A.1. Built environment factors were categorized in terms of measurement method (perceived or objective measures) and scale (micro, meso, or macro). Microscale environment is that immediately surrounding the respondents, such as streetscape and cycling path design; mesoscale environment refers to the medium-scale environments in which respondents lived, such as neighborhoods or census tracts; and macroscale environment refers to large environments such as cities or countries. We identified 12 built environmental factors from the 39 papers covered in our review study (Fig. 2): density, land use mix, availability of non-residential destinations, accessibility of public transport, street connectivity, availability of green spaces, terrain slope, aesthetics/attractiveness, presence of cycling paths and facilities, cycling safety design features, cycling paths/minor roads length, and composite variables. The classification followed and developed from previous reviews (Day, 2016; Saelens and Handy, 2008; Wang et al., 2016).

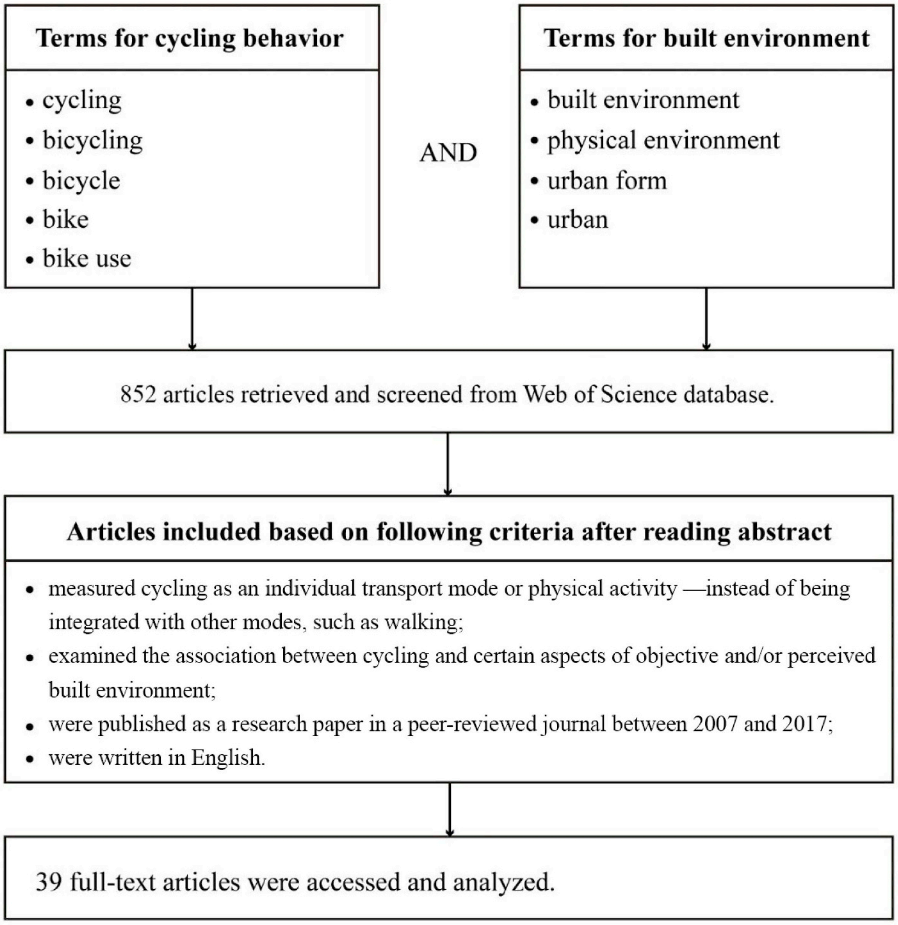

Fig. 1. Workflow of the literature review.

Table 3 is extracted from Table A.2; it underlines the directions of built environment-cycling associations (e.g. expected, unexpected/null). Based on planning theory and previous literature, a greater or better condition of a built environment factor was "expected" to associate with a higher level of cycling behavior (Saelens and Handy, 2008). For terrain slope and slope-related factors, a negative association with cycling was marked as expected, whereas a positive association was regarded as unexpected. For the other 11 factors, positive associations were marked as expected, whereas negative associations were marked as unexpected. Any insignificant associations were marked as null (Saelens and Handy, 2008).

Based on the data collected on cycling purposes, four domains of cycling were identified: transportation, commuting, recreation, and general cycling, followed by the physical activity domains defined in Day's study (Day, 2016). Cycling for transportation purposes was defined as the use of bicycles to travel from one place to another, while cycling for commuting purposes was defined as traveling from home to a place of work or study (Herlihy, 2011). We categorized commuting cycling as an individual domain because many empirical studies treat it as a separate outcome, although commuting is usually classified as one subtype of transportation. Cycling for recreation was defined as the voluntary use of a bicycle for satisfaction, pleasure, or creative enrichment (Horner and Swarbrooke, 2005). Studies that did not clearly indicate cycling purposes were classified as general cycling.

2.4. Weighted average elasticity values of built environmental factors

We calculated elasticity values from the 39 studies and then computed the average elasticities weighted by sample size for all 12 factors (see Table 4). The elasticity values were unit-free measures of the magnitude of built environment-behavior associations, making it possible to compare the effect size of different built environment factors from various studies with different social and built environment contexts and different estimating techniques for both built environmental factors and cycling behaviors. Elasticity is defined as the percentage change in a variable associated with a 1% increase in another interest variables, and has been widely used in recent sensitivity analyses, especially of the built environment and in travel mode studies (Munshi, 2016; B. D. Sun et al., 2017; Zhang, 2004). For instance, if a 1% increase in population density is associated with a 0.3% increase in cycling time, then the elasticity value will be 0.3.

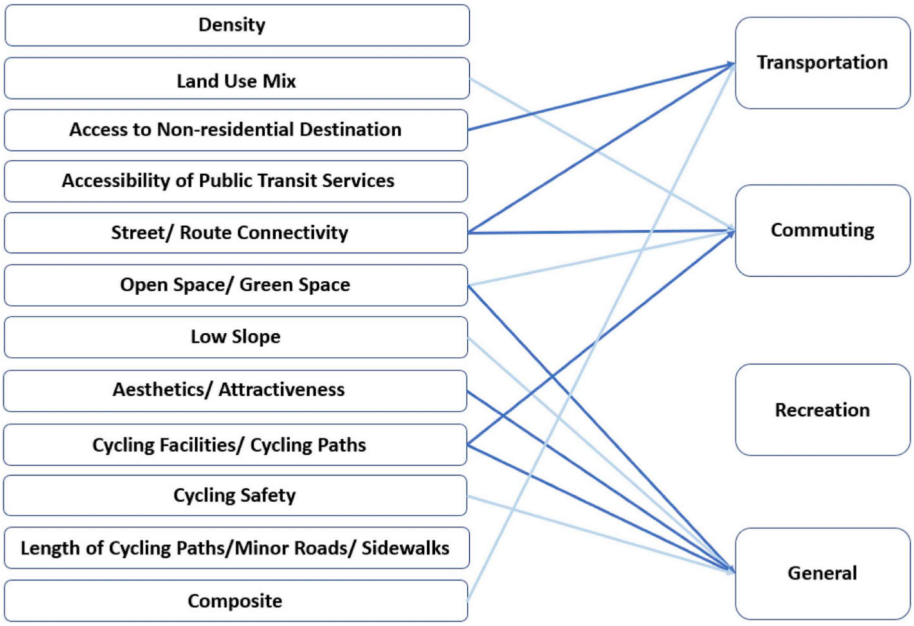

Fig. 2. The strengths of associations between built environmental factors and different cycling purpose. Strong associations (the number of expected results was greater than twice the sum of unexpected and null results) are shown as dark blue lines. Emerging associations (where the number of expected results was more than the sum of unexpected and null results but less than twice of the sum) are shown as light blue lines. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Elasticity calculation formulas.

Regression model	Elasticity Formula
Linear	$\beta \times \frac{\bar{X}}{\bar{Y}}$
Log-log	β
Logistic	$\beta \times \bar{X} \times \left(1 - \frac{\bar{Y}}{n}\right)$

Note: β is the regression coefficient on the built environment factors in a specified study. $\bar{Y}$ refers to the mean value of the cycling behavior in a specified study, and $\bar{X}$ refers to the mean value of the built environment factors. $\frac{\bar{Y}}{n}$ is the mean estimated probability of occurrence.

Table 2
Number of studies available for the computation of weighted average elasticity by sample size. Weighted elasticity values were calculated if there were at least three candidate studies (shown in the bolded font).

	Number of Available Studies			
	Transport	Commuting	Recreation	General
Density	**4**	0	0	0
Land use mix	**3**	0	0	0
Availability of non-residential destinations	1	0	0	0
Accessibility of public transport	0	0	0	0
Street connectivity	**4**	**4**	0	0
Availability of green spaces	1	0	0	**3**
Terrain slope	0	0	0	**3**
Aesthetics/attractiveness	1	0	0	0
Presence of paths and facilities	**5**	**3**	0	**3**
Cycling safety design features	**6**	0	0	0
Cycling paths/minor roads length	0	0	0	0
Composite variables	0	0	0	0

Table 3
Strength of association grouped according to environmental factors and domains of cycling and expected evidence (+), unexpected evidence (−) and null (0) results. One study may have multiple results. Strong evidence (where the number of expected results was more than twice the sum of the unexpected and null results) is shaded in dark blue; emerging evidence (where the number of expected results was more than the sum of unexpected and null results but less than twice of the sum) is shaded in light blue.

	Transportation			Commuting			Recreation			General		
Built Environment Factors	+	–	0	+	–	0	+	–	0	+	–	0
Density	3	6	2	0	1	2	1	3	1	2	4	1
Land use mix	7	8	1	2	1	0	0	6	1	2	3	0
Availability of non-residential destinations	5	1	1	1	1	0	0	1	3	1	2	1
Accessibility of public transit	1	3	1	0	2	1	0	0	0	0	3	2
Street connectivity	11	2	3	3	0	1	4	2	2	2	1	6
Availability of green spaces	4	5	2	2	1	0	1	1	1	3	1	0
Terrain slope	2	2	2	1	1	0	0	2	0	3	1	1
Aesthetics/attractiveness	3	6	1	1	1	0	0	3	2	3	0	1
Presence of cycling paths and facilities	5	7	2	5	1	1	0	2	1	5	0	0
Cycling safety design features	10	12	3	3	4	0	1	5	2	4	2	1
Cycling paths/minor road lengths	1	2	1	1	1	0	0	3	1	0	1	2
Composite variables	2	1	0	1	1	0	0	1	0	0	1	0

Table 4
Weighted average elasticity values of built environment factors.

	Elasticity value			
	Transport	Commuting	Recreation	General
Density	< 0.01	–	–	–
Land use mix	0.09	–	–	–
Availability of non-residential destinations	–	–	–	–
Accessibility of public transit	–	–	–	–
Street connectivity	0.08	0.39	–	–
Availability of green spaces	–	–	–	0.27
Terrain slope	–	–	–	0.26[a]
Aesthetics/attractiveness	–	–	–	–
Availability of cycling facilities/paths	0.07	0.28	–	
Cycling safety design features	0.04	–	–	–
Cycling paths/minor road lengths	–	–	–	–
Composite variables	–	–	–	–

[a] Sign was reversed for terrain slope.

The calculations of elasticities for individual studies were conducted in one of two ways (Ewing and Cervero, 2010). We either: (1) found elasticity values reported in papers; or (2) calculated a value from regression coefficients and the mean values of dependent and independent variables. For method (2), we used the formulas in Table 1 to compute elasticity values, depending on the types of regression method used to estimate coefficient values. Using formulas to calculate elasticity from mean values may result in an error in estimated results because the difference between the mean and individual values of elasticities can be significant. Train mentioned that “the probability evaluated at the average utility underestimates the average probability when the individuals' choice probabilities are low and overestimates when they are high” (Train, 1986, p. 42). When the elasticity is calculated over a curve relationship, it refers to an arc elasticity. However, due to the limited accessibility of raw data, we nevertheless used the mean values to calculate the elasticities quoted in this review.

The weighted average elasticity of each built environment factor was calculated according to three conditions: 1) studies reported significant results of a built environmental factor; 2) studies reported descriptive statistics of dependent and independent variables, which are necessary to compute elasticity value; and 3) at least three studies were available. Number of candidate studies used to calculate weighted average elasticity values are shown in Table 2. Ten of the 39 studies included in this review for computations of weighted average elasticity used objective measurement of the built environment factors. Only one study (Ma and Dill, 2015) that used perceived measures to compute weighted average elasticity was included, while other studies using perceived measures did not report adequate descriptive statistics for elasticity calculation.

3. Results

3.1. Study sample

We reviewed 39 studies published between 2007 and 2017 focusing on associations between built environment and cycling. Most studies (33 out of 39) were conducted in developed countries; three studies were conducted in developing countries; and three studies were conducted in multiple countries including both developing and developed countries. The top three studied countries were the United States (12 studies), Belgium (10), and Australia (9). There were also studies conducted in developing countries such as Brazil

(3), China (2), Colombia (3), and Mexico (2). The criteria used to define a country as "developed" and "developing" followed the Standard Country or Area Codes for Statistical Use (M49) published by the United Nations (United Nations, 1999).

Five studies focused on children or adolescents, and four focused on older adults. In terms of sample size, over 60% of studies recruited fewer than 5000 participants, while 14 of 39 studies recruited fewer than 1000 participants. Studies conducted in multiple cities usually recruited more than 10,000 participants.

3.2. Built environment

Most of the studies (20 out of 39) focused on the impact of the built environment at mesoscale (at neighborhood level) and collected built environmental factors within a buffer of a respondent's residential locations.

3.2.1. Perceived or objective measures

In terms of the measurement of built environment factors, objective measures were used in 26 of the 39 studies; perceived measures were used in 22 studies; and perceived and objective measures were simultaneously used in 9 studies. While one paper suggested that both perceived and objective measures had distinct effects on cycling behaviors (Ma and Dill, 2015), other studies argued that the effects of perceived measures were slightly more reliable than those of objective measures (Orstad et al., 2017).

3.2.2. Data collecting method

For objective measures, Geographic Information System (GIS) technology, combined with census data and open source urban land-use data, has been widely used to identify objective built environment measures. Recent studies have also used advanced methods to improve the accuracy of measurement, such as the Normalized Difference Vegetation Index (NDVI), a greenness index based on satellite remote sensing images (Tilt et al., 2007).

For perceived measures, interviews and questionnaires were the most common data-collection methods. In particular, the Neighborhood Environment Walkability Scale (Cerin et al., 2006; Saelens et al., 2003a,b; Sallis, 2002) was the most widely used questionnaire to measure mesoscale built environments; various versions of this questionnaire have been developed and validated in different study areas. Besides standard questionnaires or interviews, one recent study has exploited the opportunities of using simulated photos to survey perceptions of proposed built environment changes (Ghekiere et al., 2015).

3.2.3. Built environment factors

In our review database, cycling safety design features (addressed in 32 of the 39 studies) were the most widely studied aspect of the built environment, followed by street connectivity (26 of 39 studies), presence of cycling paths and facilities (23 of 39 studies), and land use mix (22 of 39 studies).

3.3. Cycling

3.3.1. Domains of cycling

We found that 23 of the 39 studies examined cycling for transportation. Nine studies examined cycling for commuting and eight for cycling for recreational purposes, respectively. Ten studies focused on general cycling behaviors.

3.3.2. Data collection method

The most common method of collecting cycling data, such as cycling time and frequency, was by questionnaires. Fourteen studies used the International Physical Activity Questionnaire (IPAQ) or a modified IPAQ, whereas many other studies developed their own questionnaires. The participants were asked to report the duration or frequency of their cycling activity during a given period, and/or their willingness to cycle for different purposes.

In studies focusing on microscale built environment, some researchers used a mapping method, e.g. retracing a cycling route on a map to collect participants' cycling route choice, which is an important indicator of participants' preference of cycling environment (Snizek et al., 2013). In studies focusing on macroscale built environment attributes, such as at city level and/or across countries, the proportion of the cycling population and the count of cyclists in specific places were also widely used to measure cycling behaviors (Buehler and Pucher, 2011).

3.4. Associations between cycling and the built environment

A built environment factor was identified as strong evidence if the number of expected results was more than twice the sum of the unexpected and null results; a factor was identified as an emerging evidence if the number of expected results was more than the sum of unexpected and null results but less than twice of the sum. In terms of transportation cycling, there was strong evidence for an association with street connectivity (11 expected results vs. 5 unexpected/null), and availability of non-residential destinations (5 vs. 2), and emerging evidence for an association with a composite index (2 vs. 1) (Table 3). However, the evidence for an association with other built environment factors was weak (i.e. the number of expected results was less than or equal to the number of unexpected results).

For commuting cycling behavior, there was strong evidence of an association with street connectivity (3 vs. 1) and presence of cycling routes/paths (5 vs. 2), and emerging evidence for an association with land use mix (2 vs. 1) and availability of green spaces (2 vs. 1).

The results regarding recreational cycling behavior were less clear, partly because there were fewer of these. We did observe distinct evidence in these studies for associations between recreational cycling and any built environmental factors, although there was inconclusive evidence for an association with street connectivity, given the equal number of expected and unexpected/null results (4 vs. 4).

For general cycling behavior, strong evidence was found of an association with the presence of cycling routes/paths (5 vs. 0), open space and green space (3 vs. 1), and aesthetics and attractiveness (3 vs. 1); and emerging evidence was found for an association with terrain slope (3 vs. 2), and cycling safety design features (4 vs. 3).

3.5. Elasticity values of built environmental factors

We calculated elasticity values from individual studies in our review database. Table 3 shows the weighted average elasticity values of 12 built environmental factors on different domains of cycling. For transport cycling, land use mix had the largest elasticity value of 0.09, which meant that a 1% increase in land use mix was associated with a 0.09% increase in cycling for transport. Street connectivity had the second largest elasticity value of 0.08, while other factors had relatively small elasticity values below 0.05. For commuting cycling, both street connectivity (0.39) and availability of cycling facilities/paths (0.28) have relatively large elasticity values.

4. Discussion

In this study, we conducted an updated review of the associations between the built environment and cycling behaviors based on 39 empirical studies conducted in 2007–2017. The results showed that different domains of cycling behaviors (transport, commuting, recreation, and general) may have different associations with built environment factors. Consistent and positive associations were found between street connectivity and cycling for transportation and commuting purposes, which suggests that street connectivity may be a fundamental requirement for cycling behaviors. The presence of cycling paths and facilities and open/green spaces was associated with both commuting and general cycling behaviors, which suggests that these two factors are more important for commuting cycling than other domains.

The land use mix, availability of paths to non-residential destinations, and composite variables are only associated with certain domains of cycling, and show less evidence of an association with general cycling. By contrast, low slope and cycling safety are only associated with general cycling but show less evidence of association with any specific domains. However, it is still difficult to draw definitive conclusions about these specific associations given the limited number of available studies. A future review of a sufficient number of studies, especially those simultaneously considering different domains of cycling behaviors, is warranted; such a review may unequivocally demonstrate the relationship of particular built environment characteristics with particular cycling behaviors (Ferdinand et al., 2012).

4.1. Comparison with previous reviews

Previous reviews suggested that land use mix and provision of bicycle parking facilities may increase the likelihood of engagement in general cycling (Saelens et al., 2003a,b; Wang et al., 2016). We found strong evidence in results from studies during 2007–2017 for associations between general cycling and availability of green spaces, terrain slope and availability of cycling facilities/path. All three factors had relatively large elasticity values.

Previous reviews found significant associations between transport cycling behaviors and the presence of cycle routes/paths, high population density, availability of non-residential destinations, and availability of green space, and terrain slope (Fraser and Lock, 2011; Heinen et al., 2010; Saelens et al., 2003a,b). The results of the 2007–2017 studies regarding transport cycling found strong associations with street connectivity, and emerging associations for the influence of availability of non-residential destinations and composite factors upon cycling behaviors, although the elasticity values for these factors was relatively small.

For commuting cycling, previous reviews document strong associations with land use mix (Heinen et al., 2010). This review also found evidence of consistent associations between commuting cycling and land use mix, and constant associations with the availability of green space, street connectivity, and presence of cycling paths and facilities. The latter two factors also had relatively large elasticity values. This indicates the great importance of land use mix and green spaces and the increasing importance of street connectivity and cycling paths/facilities in promoting commuting cycling.

However, the recreational cycling findings of the 2007–2017 studies showed no clear association with most of the environmental factors. The unexpected/null results outnumbered expected results for any environmental factors, which echoed findings from previous reviews (Day, 2016; Saelens et al., 2003a,b).

In contrast with the findings of previous reviews, our review did not reveal a clear association between cycling behaviors and urban density. This contrasting result may be explained by increased ranges of urban density arising from a broader scope of geographical locations covered in this review. That is, this review included studies conducted in both developed and developing countries, while previous reviews included only studies conducted in developed countries (Christiansen et al., 2016). In addition, cities classified as "high density" in China and South America may be several times denser than "high-density" cities in Europe, North America and Australia. Indeed, researchers have recently indicated that different ranges of urban density may account for the inconsistent influence of urban density on physical activity (Gomez et al., 2010; Lu et al., 2017; Su et al., 2014; Szeto et al., 2017).

4.2. Objective measures vs. perceived measures

In addition to more evidence of associations between the built environment and cycling, studies in the past decade have incorporated significant methodological developments in addressing some limitations raised in previous reviews (Christiansen et al., 2016; Cole-Hunter et al., 2015; Day, 2016; Fraser and Lock, 2011; Ma and Dill, 2015). One such development was to explore the relationship between the objective and perceived built environment. The objective measures of built environment factors are often obtained from existing GIS data or field audits, while perceived measures are often collected based on an individual's perception of built environment features (Brownson et al., 2009). The results obtained from objective measures can be repeated and hence are more reliable than results from perceived measures. However, perceived measures reflecting individual exposure and perceptions of the built environment, and thus may complement and inform studies based on objective measures (Ma and Dill, 2015). For example, safety and aesthetics are typically assessed by subjective measures, but objective measurement of these factors is warranted in further studies.

4.3. Bikeability and walkability

As mentioned at the beginning of this review, researchers have debated whether built environment factors promoting walking also promote cycling (Muhs and Clifton, 2016). Previous reviews suggested that higher-density neighborhoods with more diverse land use and greater street connectivity may promote walking behaviors (Saelens and Handy, 2008; Wang et al., 2016). However, we did not find a close relationship between walkability and bikeability, as only street connectivity was positively associated with cycling. Recent empirical studies investigating walking and cycling simultaneously have also argued that walking and cycling are affected by different built environment factors, and to a different extents (Muhs and Clifton, 2016; Ton et al., 2019).

4.4. Planning and policy applications

This meta-analysis provides the elasticity values of various built environment measures on cycling behaviors from pooled samples. These values may be useful for urban planners and policymakers for providing rough forecasts on baseline cycling behaviors for new urban design projects, or of potential changes in cycling behaviors after design interventions in existing urban areas. Previous reviews have already suggested the utilization of elasticities, and the new elasticities calculated in this review could also be used in similar situations (Cervero, 2006; DKS Associates, 2007; Johnston, 2004; Walters et al., 2000). Furthermore, a potential application of elasticities may be to estimate health outcomes. Knowledge of regular cycling behaviors, as a common form of physical activity, is critical to predicting health conditions. Therefore, a potential increase in cycling can be used to project the potential health impacts of urban design interventions. Similarly, it can also be used to estimate the reduction of greenhouse gas emissions or air pollution, because cycling can reduce private vehicle use.

4.5. Limitations

There are three limitations to this review. First, because we only reviewed articles written in English, the results of research written in other languages were not considered. However, this review has covered a broader range of geographical locations, including both developed and developing countries, whereas previous reviews largely focused on developed countries (Christiansen et al., 2016).

Second, only five studies covered in this review involved children or adolescents. Being active during childhood has been found to decrease several health risk factors and enhance quality of life in later years (Aires et al., 2011; Bailey et al., 2012; Maki-Opas, de Munter, Maas, den Hertog and Kunst, 2014). Future studies should thus pay more attention to children's and adolescents' cycling behaviors, due to the increasing trend of obesity among young people (Cai et al., 2017).

Third, it was still a challenge to assess causality from the 2007–2017 studies. Most recent studies have used cross-sectional research design, making it difficult to determine whether the built environment alters residents' cycling behaviors or if cyclists choose to live in areas with cycling-supporting built environment characteristics. To address this limitation, natural experiment research designs should be implemented to examine causal relationships. For example, researchers from Perth made an attempt to address this issue by conducting a RESIDE project, a longitudinal natural experiment to compare cycling behaviors of people before and after moving into a new residence (Badland et al., 2013). The results demonstrated that changes in both objective and self-reported built environment characteristics were associated with changes in transport cycling and recreational cycling. This longitudinal experimental design enabled the researchers to study the effects of neighborhood design on cycling behaviors while controlling for individual attitudes toward cycling and other health-related behaviors.

4.6. Future directions

As objective measurements of built environments can avoid potential bias in self-reported data, big data in conjunction with machine learning techniques offer unprecedented opportunities for objectively measuring fine-grained built environment characteristics. Open source data have been widely used in recent urban studies (Cole-Hunter et al., 2015; Hino et al., 2014; Y. R. Sun et al., 2017). OpenStreetMap, Points of Interest, and Google Street View (GSV) provide plenty of opportunities to quantify built environment metrics, such as street networks and streetscapes (Lu, 2018; Y. R. Sun et al., 2017; Wang et al., 2019a, 2019b). Computer vision is one of the most popular machine learning applications and is used mainly for object recognition. GSV and other image databases can help researchers to develop image recognition methods to measure the built environment. SegNet is a notable application developed by the University of Cambridge: it is a fully convolutional deep neural network architecture for semantic pixel-wise segmentation, trained to classify urban street images into 12 categories, such as 'sky', 'building', 'road', 'pavement', and 'tree', enabling much more reliable assessment of the percentage of streetscape design elements (Badrinarayanan et al., 2017). Researchers have also developed several objective variables to measure urban greenness, such as NDVI, measured using high-solution satellite remote images, and GSV eye-level greenness (Cole-Hunter et al., 2015; Lu et al., 2018). The advance of machine learning methods may significantly improve the accuracy of estimating a person's environment exposure (e.g. eye-level greenness, building density), and is more time- and cost-effective than field audits.

As perceived data can reflect individual exposure and perceptions of the built environment, it would be better for such data to be measured objectively. To this end, portable sensing technologies, notably GPS technology, have enhanced the capacity for recording, measuring, and analysis of human behaviors, and use of these would thereby avoid the bias of self-reported built-environment data. The emergence of advanced equipment, such as eye tracking or mobile electroencephalography, may enable the assessment and recording of the psychological impact of environments on individuals, and hence provide opportunities for researchers to develop an enhanced understanding of the relationship between the perceived environment and cycling behaviors (Mavros et al., 2016).

Such technological advancement may also reduce the cost of collecting detailed behavioral data. Crowd-sourced GPS data and physical-activity apps are emerging methods of collecting large samples of cycling data (B. D. Sun et al., 2017). However, the extent to which app users represent the total population of cyclists in a given city remains unclear (Selala and Musakwa, 2016). In China, public bicycle-sharing programs have attracted millions of people back to cycling. These shared bicycles are usually equipped with GPS technology and the data of the routes on which these bicycles are taken are collected (Tsing Hua University Planning and Design Institution and Mobike, 2017). Such data may help researchers use large sample sizes to further explore the association between the built environment and cycling behaviors.

Most of the 2007–2017 studies were still conducted in cities of Europe, North America, and Australia, although some emerging studies were conducted in cities of developing countries, such as Brazil, China, Colombia, and Mexico. Future studies should pay more attention to the cities of Asia and South America, where governments are investing in cycling infrastructure and cycling is becoming more and more popular. Furthermore, given the fact that cycling behaviors may be influenced by local culture and vehicle ownership, the studies conducted in a broader range of geographical locations may improve our understanding of the relationships between the built environment and cycling in diverse urban and cultural contexts.

This review focused on the unique characteristics of cycling, and studies with the same research framework will provide better guidance for policymakers, urban planners and designers in creating a cycling-friendly urban environment, including more specific recommendations for different demographic groups and different cities.

5. Conclusion

This review summarizes the recent evidence (2007–2017) of the relationship between cycling and various built environment characteristics. A positive and consistent correlation between street connectivity and cycling for commuting and other transportation purposes was found. In addition, the presence of cycling paths and facilities was found to be positively associated with both commuting cycling and general cycling. There were weak or mixed associations with other built environment factors, such as land use mix and density. With the emergence of advanced measurement methods, future studies should overcome current limitations and support improved urban planning and public-health practice to increase uptake of cycling.

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Appendix A

Table A.1
Characterization of studies by country, sample, built environmental data source, built environmental factors, analyzed geographic unit, cycling metrics, controlled variables, self-selection controlled or not, and major results.

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
1 Ghekiere et al. (2015)	Belgium	305 fifth and sixth grade children and their parents from twelve randomly selected primary schools	Panoramic color photographs	1. Evenness of cycle path 2. Degree of separation from motorized traffic 3. Speed limit for motorized traffic	Individual respondent	Route choice from children and their parents respectively	SE	Yes	Preference of children: 1. Evenness of the cycle path 2. Lower speed limitation. Preference of parents: 1. Lower speed limitation 2. Degree of separation with motorized traffic
2 Titze et al. (2008)	Austria	905 inhabitants aged 15–60 years from Graz	Interview	1. Attractiveness of cycling conditions 2. Land use mix-diversity of uses 3. Safety from traffic 4. Bike lane connectivity 5. Presence of steep elevation 6. Presence of streetlights during night 7. Presence of sidewalk 8. Home: bicycle parking 9. Destination: bicycle parking	Individual respondent	Share of cycling	SE/OT	No	Lane connectivity, the presence of a steep elevation were positively associated with bicycling for transportation.
3 Sylvia Titze et al. (2010)	Australia	1813 participants age range 18–78 years from Perth	Neighborhood Environment Walkability Scale	1. Access to services (land use mix-access) 2. Neighborhood surroundings green and attractive 3. Bicycle/walking paths accessible 4. Number of destinations for transport cycling 5. Number of destinations for recreational cycling 6. Many traffic slowing devices 7. Presence of many 4-way intersections	Neighborhood	1. Times of cycling for transport per week 2. Times of cycling for recreation per week	SE/AT	Yes	1. Leafy and attractive neighborhoods, access to bicycle/walking paths, the presence of traffic slowing devices and having many 4-way street intersections were positively associated with cycling for transport. 2. The perception of alternative routes for getting from place-to-place significantly increased the odds of cycling for recreation compared with low

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Table A.1 (*continued*)

	Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
					8. Presence of many alternative routes 9. Major barriers in local area 10. Absence of cul-de-sacs					perceived prevalence of alternative routes.
4	Ma and Dill (2015)	America	902 adults from Portland	Survey, Regional Land Information System (RLIS) from Portland Metro, Region's transportation and land use planning agency, U.S. Census Bureau	1. Perception of off-street bike paths 2. Perception of bike lanes 3. Perception of quiet streets easy for bike 4. Perception of many bike destinations nearby 5. Miles of off-street bike path within 1/2-mile buffer 6. Miles of bike lane within 1/2-mile buffer 7. Miles of minor street within 1/2-mile buffer 8. # Retail jobs (000) within 1/2-mile buffer	Neighborhood	Number of days of cycling for commuting or transportation over the past month	SE/OT/AT	Yes	1. Respondent would have been more likely to bicycle for transportation if they perceived that there are many bikeable destinations near their home. 2. Respondent would have been more likely to bicycle for transportation if miles of minor streets is longer. 3. Perceived and objective built environment have independent effects on the bicycling propensity.
5	Owen et al. (2010)	Australia and Belgium	2159 participants aged 20–65 years from Adelaide (Australia), and 382 participants aged 18–65 years from Ghent (Belgium)	Adelaide: Census Collection Districts (CDs) via GIS database Ghent: Survey, Neighborhood Environment Walkability Scale Questionnaire	Adelaide: 1. Dwelling density 2. Street connectivity 3. Land use mix 4. Net retail area ratio to conduct a walkability index. Ghent: 1. Residential density 2. Land use mix (distance to facilities) 3. Connectivity	Neighborhood	Number days of cycling for transport in a week (at least 10 min)	SE	No	1. Adelaide, people living in a higher-walkable community had 82% higher odds of regular bicycle use for transport. 2 Ghent, people living in the higher and highest walkability neighborhoods had approximately a 2.5 times higher likelihood to bicycle for transport
6	Winters et al. (2016)	Canada and America	5664 census tracts in 24 US and Canadian cities	Walk Score	1. Bike Lane Score 2. Hill Score 3. Destinations and Connectivity Score	1. Neighborhood 2. City	Share of cycling for commuting	OT	No	At the census tract level, a ten-unit increase in Bike Score was associated with a 0.5% increase in the proportion of population cycling to work

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
7 Hino et al. (2014)	Brazil	1206 adults aged above 16 years from Curitiba	GIS	1. Bus stop number 2. BRT tube stations number 3. Traffic safety number 4. Entropy (land use heterogeneity) 5. Residential area proportion 6. Commercial area proportion 7. Street density 8. Number of blocks 9. Average length of the streets 10. Dead-end streets proportion 11. Street intersections (≥4 way) proportion. 12. Slope 13. Bike path density 14. Distance to nearest bus stop 15. Distance to nearest BRT tube station 16. Distance to nearest bike path	Neighborhood	Duration time of cycling for transportation per week (mins)	SE	No	Greater number of traffic lights, and higher land use mix were inversely associated with cycling.
8 Chen et al. (2017)	America	bicycle count data collection in 5 years from Seattle	Seattle Department of Transportation and Puget Sound Regional Council	in a 1-mile, 0.5-mile, 0.25-mile buffer, 1. The sum of bike lane length, in miles; 2. The percent of steep areas in buffers, in %; 3. The percent of water spaces in buffers, in %; 4. The percent of commercial and mixed land use in buffers, in %; 5. The percent of residential lands in buffers, in %; 6. The entropy of six types of land use, in%; 7. The percent of green spaces and parks in buffers, in %;	Neighborhood	Counts of bicycle at intersections	WE/OT	No	1. Bicycle counts are greater in zones with more mixed land use, a higher percentage of water bodies, or a greater percentage of workplaces; 2. The increments of bicycle infrastructure is positively associated with the increase of bicycle volume; 3. Bicycle counts are fewer in steep areas

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
				8. The percent of offices and governments in buffers, in %; 9. The number of employments per square mile 10. The number of households per square mile					
9 Winters et al. (2010)	Canada	1902 adults aged above 19 years from Metro Vancouver region	1. Census, 2. Academic research projects, 3. Property tax assessment authority 4. Regional transit authority 5. GIS	1. % of land area with green cover; 2. Variation in elevation (hilliness); 3. % road segments with slope 95% (steep hills); 4. Ratio of 4-way intersections to all intersections; 5. % of road network that is Highway; 6. % of road network that is Arterial road; 7. % of road network that is local road; 8. % of road network that is off-street path; 9. % of road network that is Designated bike route; 10. Presence of Traffic calming features; 11. Presence of Road markings or signage for cyclists; 12. Presence of crossings with cyclist-activated traffic lights; 13. Population per hectare; 14. Land use mix; 15. % of land use that is single family residential; 16. % of land use that is multiple family residential;	Zone of route, origin and destination	1. The most frequent non-recreational bicycle trip (if any), 2. Any other non-recreational bicycle trip (if any)	SE	No	Increased odds of bicycling were associated with 1. Less hilliness; 2. Higher intersection density; 3. Less highways and arterials; 4. Presence of bicycle signage, traffic calming, and cyclist-activated traffic lights; 5. More neighborhood commercial, educational, and industrial land uses; 6. Greater land use mix; 7. Higher population density.

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
				17. % of land use that is Commercial; 18. % of land use that is Educational; 19. % of land use that is Entertainment; 20. % of land use that is Industrial; 21. % of land use that is Office; 22. % of land use that is Park.					
10 Mertens et al. (2017)	Belgium, France, Hungary, The Netherlands and the United Kingdom	6037 individuals aged above 18 years from Ghent region (Belgium), Paris region (France), greater Budapest (Hungary), Randstad region (The Netherlands) and Greater London (the United Kingdom)	SPOTLIGHT Virtual Audit Tool (s-VAT)	1. Presence of traffic calming features (such as speed humps, traffic island, roundabouts or traffic lights); 2. Speed limit ≤ 30 km/h; 3. Absence of bicycle lanes; 4. Cars that form an obstacle on the road; 5. Presence of green and water areas; 6. Presence of trees; 7. Presence of litter.	Neighborhood	in the last 7 days: 1. Number of days 2. Duration time (average time/day) of cycling for transport	SE	No	1. Living in a neighborhood with more streets where the speed limit is ≤ 30 km/h, more parked cars that form an obstacle on the road, more trees, or more litter were all associated with being more likely to engage in cycling for transport. 2. Living in a neighborhood with more traffic calming features, or fewer bicycle lanes, was associated with being less likely to engage in cycling for transport. 3. Living in a neighborhood with more cars that form an obstacle on the road was associated with more minutes of cycling for transport per week. 4. Living in a neighborhood with more trees was associated with fewer minutes of cycling for transport per week.

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
11 de Vries et al. (2010)	Netherlands	1228 children aged 6–11 years from 10 disadvantaged neighborhoods in Haarlem, Rotterdam, Amersfoort, Schiedam, Vlaardingen, Hengelo.	Observation based on a modified Neighborhood Environment Walkability Scale	1. Proportion of residents to enterprises, 2. Proportion of green space to residents, 3. Frequency of unoccupied houses 4. Presence of green space 5. Presence of water 6. Frequency of 14 items on walking and cycling infrastructure 7. General impression of the activity-friendliness of the neighborhood	Neighborhood	in the last 7 days, the number of hours of cycling to school and cycling for transport	SE	No	1. For cycling for transportation, significant correlates were the number of recreation facilities and the frequency of pedestrian crossings; 2. Cycling to school was strongest associated with the number of recreation facilities, the presence of green space, and the frequency of pedestrian crossings, traffic lights, and parallel parking spaces in the neighborhood;
12 Emma J Adams et al. (2013)	United Kingdom	3516 participants from Cardiff, Kenilworth and Southampton	Assessing Levels of Physical Activity and Fitness European environmental questionnaire	1. Cycling safe from traffic 2. Safe to cross roads 3. Convenient walk/cycle routes 4. Cycle lanes/routes 5. Variety of walk/cycle routes 6. Pleasant to walk/cycle 7. Places to walk/cycle to 8. Open spaces 9. Free from litter 10. Many road junctions	Neighborhood	Time duration (in hours and minutes) and the total distance of cycling for transport and cycling for recreation.in past week	SE/OT	No	Cycling for transport was associated only with street connectivity.
13 Heesch et al. (2014)	Australia	10,233 adults aged 40–65 years in Brisbane	Abbreviated version of the Neighborhood Environment Walkability Scale	1. Aesthetics 2. Many traffic calming devices 3. Many streets are hilly 4. Many cul-de-sacs 5. Many 4-way intersections	Neighborhood	1. Frequency of cycling for recreation or exercise in the last 12 months 2. Time duration (hours and minutes) of cycling for transport in the last week'	SE	Yes	Little crime, few cul-de-sacs, nearby transport and recreational destinations were associated with utility cycling.

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Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
14 Heesch et al. (2015)	Australia	11,036 adults aged 40–65 years from Brisbane	MapInfo GIS database and Map Info Professional	1. Count of 4-way or more intersections 2. Hectares of tree coverage from aerial photography 3. Km of off-road cycleways 4. Count of street lights 5. Standard deviation of hilliness 6. Average residential parcel size in square meters 7. Degree to which there is a mix of land use 8. Network distance to CBD 9. Network distance to nearest ferry stop 10. Network distance to nearest river 11. Network distance to nearest shop 12. Network distance to nearest train station 13. Network distance to nearest coastline	Neighborhood	1. Time duration of cycling for transport in the last week 2. Frequency of cycling for recreation in last 12 months	SE/OT	Yes	1. Residents living < 10 km(network distance) from the Brisbane CBD or from the nearest ferry stop had an increased likelihood of cycling for transport. 2. Residents who lived > 5 km from the Brisbane River were less likely to cycle for transport than were those who lived < 3 km from the river. 3. Living in a neighborhood with a moderately high amount of tree coverage or of bike paths(Quartile 3) was associated with decreased likelihood of recreation-only cycling compared with living in a neighborhood with the highest amounts of these attributes. 4. Residents living < 3 km from the CBD were more likely to cycle for recreation-only compared with those living > 10 km from that location. 5. Residents living < 1 km from the closest shops were less likely to cycle for recreation-only compared with those living > 1 km from these shops. 6. Living 3–5 km from the closest train

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
									station decreased the likelihood of cycling for recreation-only. 7. Those living < 5 km from the coast had an increased likelihood of recreation-only cycling compared with those living > 10 km from the coast.
15 Forsyth and Oakes (2014)	America	703 participants aged above 24 from the Minneapolis-St. Paul area of Minnesota	1. Existing land use and business databases 2. Aaerial photo interpretation 3. Fieldwork, processed using the ArcGIS, 4.Survey	1. Population/land area (network of 200 m, 400 m, straight line of 200 m) 2. Population/developed land area (400 m network, 200 m straight line) 3. Population and employment/land area (400 m network, 200 m straight line) 4. Housing units/unit land area (200 m network, 400 m network) 5. Parcel area: Industrial (%) (400 m network) 6. Parcel area: Parks/Rec (%)(1,600 m straight line) 7. Parcel area: Industrial and auto-oriented uses (%) (400 m network) 8. Street segments with visible litter, graffiti, or dumpsters (%) (200 m network) 9. Residential Population/residential parcel area 10. Lot coverage 11. Median census block area 12. Intersections per unit area	Individual respondent	1. Number of days and duration time of cycling at least 10 min during the last 7 days. 2. Trips between two places with distances recorded in miles or blocks. 3. State the most recent time they had ridden in neighborhood if people had cycled in their neighborhood in the past two years	SE/OT	No	1. More cycling occurred where people lived industrial, auto-oriented land uses, and in areas with visible litter and graffiti. 2. In a buffer of 1600 m the park area is associated with total miles cycled 3. Lower densities, larger blocks, fewer sidewalks, and fewer bus stops are associated with the frequency of cycling, those living in lower density areas cycling more.

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Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
				13. Median perimeter of block 14. Proportion of dissimilar land uses among grid 15. Sidewalk length/road length 16. Transit stop density 17. Access to services 18. Places for walking and cycling 19. Neighborhood surroundings/attractiveness 20. Safety from traffic					
16 Buehler and Pucher (2011)	America	90 of the 100 largest U.S. cities as determined by population estimates of the 2008 American Community Survey	The League of American Bicyclists and the Alliance for Biking and Walking	1. Miles of bike lanes in city per 100,000 population 2. Miles of bike and shared-use paths in city per 100,000 population 3. Regional index combining 22 variables measuring residential density, land use mix, strength of downtowns, and connectivity of street network,	city	1. Share of cycling for commuting in each city; and 2. The numbers of bike commuters per 10,000 population	SE/WE/LS	No	Cities with a greater supply of bike paths and lanes have significantly higher bike commute rates
17 Moran et al. (2015)	Israel	573 children aged 10–12 years (fifth or sixth grade) from Rishon LeZion	GIS	In a 400 m buffer, 1. Residential density (number of households per square kilometer), 2. Built coverage (overall built area per built lots area) 3. Street connectivity (number of intersections per square kilometer) 4. LUM measures: a. Route distance to nearest store b. Route distance to nearest park	Neighborhood	1. Cycling to neighborhood destination at least one time a week 2. Cycling for leisure at least one time a week	SE	Yes	Living in an area with low residential density is associated with the increased odds of both cycling to neighborhood and leisure cycling

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Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
				c. Route distance to school					
18 Sallis et al. (2013)	America	1780 adults aged 20–65 recruited from the Seattle, Washington and Baltimore, Maryland regions	1. GIS 2. Neighborhood Environment Walkability Scale	1. Neighborhood streets are hilly, walking is difficult 2. Bike/pedestrian trails are easy to get to 3. Safe to ride bike in neighborhood 4. Residential density 5. Land use mix-diversity 6. Land use mix-access 7. Street connectivity 8. Walking/cycling facilities 9. Neighborhood aesthetics 10. Pedestrian/traffic safety 11. Net residential density (ln-transformed) 12. Intersection density 13. Retail floor area ratio 14. Land Mixed use 15. Walkability index	Neighborhood	Bicycling frequency	SE	No	Higher riding frequency is associated with 1. Having bike/pedestrian trails easy to get to, 2. Greater safety for riding in the neighborhood 3. Greater land use mix-access. 4. Neighborhood walkability measures within 1 km were not consistently related to bicycling.
19 Nielsen et al. (2013)	Denmark	9128 cyclists aged 10–85 years from Danish National Travel survey	1. Danish building register 2. Corine land cover datasets 3. Navteq road network 4. Digital elevation model	in a 500 m and 1500 m buffer 1. Density of population, jobs and retail jobs. 2. The perception of use of land for urban areas; forest and nature areas; land use variation based on 44 land use classes, the blend of population, jobs and retail. 3. Number and density of three-way intersections; the composition of the road network (traffic roads, distributor roads, and local roads); and the proportion of buildings in the area that were	Neighborhood	Distance of cycling trips per day	SE/OT/ST	Yes	1. Flat terrain, short-distance to retail concentrations, as well as population density and network connectivity within a 1.5 km 'personal' neighborhood, all contribute to an increased likelihood of cycling. 2. Public transportation access and level-of-service, measured as the location of a train station within 1000 m and the number of daily bus and train departures within 500 m of the home,

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Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
				built before 1950 is used as an indicator of parameterization urban design. 4. Access to the nearest primary school and grocery shops, access to job and retail concentrations of sizes and scales. 5. Public transportation stops and train and bus departures by stop 6. On-site land use intensity distance to a motorway ramp or large road.					both reduce the likelihood of cycling. 3. Retail jobs per resident within a very convenient 500 m walking range indicates main streets and central area locations, and together with the network connectivity within the 500 m range, is negatively correlated to the probability of cycling. 4. Long distances to large retail concentrations, high population density, and high network connectivity within walking range are related to short daily cycling distances.
20 Van Holle et al. (2014)	Belgium	59 adults aged 45–64 years resided in semi-urban (300–600 inhabitants/km2) or urban (600 inhabitants/km2) neighborhoods from Brussels	Panoramic color photographs of semi-urban and urban streetscapes	1. Openness of view 2. Cycle path width 3. Cycle path evenness 4. Presence of driveways crossing cycle path 5. Safety crossing the street 6. Presence of historic elements 7. Presence of new elements 8. Vegetation 9. Upkeep of the cycle path 10. Upkeep of the sidewalk 11. General upkeep 12. Natural surveillance 13. Land use 14. Number of traffic lanes 15. Separation cycle path and sidewalk	Individual respondent	Time duration (mins) of cycling for transportation per week	SE	Yes	Presence of vegetation was the most important environmental characteristic to invite people for engaging in transportation cycling.

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Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
21 Sun et al. (2017)	Scotland	13684 Strava cyclists in Glasgow Clyde Valley Planning Area	1. OpenStreetMap 2. Strava Metro dataset 3. Scotland's 2011 census data 4. DATA.GOV.UK 5. European Environment Agency 6. The UK Department for Transport	1. Distance to city center 2. Distance to the nearest bus stop 3. Road length 4. Connectivity of major road 5. Connectivity of minor road 6. Road class 7. Land use mix 8. Dominant land use type 9. Contiguity to green space 10. Volume of motor vehicles 11. Traffic accident density 12. Population density 13. Employment density	Individual respondent	Recreational Cycling Rate (RCR), the rate of recreational trips during a 1-h time slot	SE	No	1. Road length has a significant and negative association with RCR 2. Both connectivity of major road and connectivity of minor road are positively and significantly associated with RCR. 3. Of the dominant land use type, "Residential" has a significant and positive association with RCR.
22 Zahabi et al. (2016)	Canada	Origin–destination (O–D) survey data from Greater Montreal in the year 1998(n = 21,188), 2003(n = 20,170) and 2008(n = 19,508)	Statistics Canada for census years, Montreal and Vélo Québec, Desktop Mapping Technologies Inc., GIS	in 500 m grid system, 1. Population density; 2. Employment density; 3. Cycling network density; 4. Public transit accessibility; 5. Land-use mix 6. Intersection (node) density 7. Street density 8. Link to node ratio 9. Distance to cycling infrastructure	Neighborhood	Share of cycling choice	SE	Yes	1. A 10% decrease in distance to nearest cycling facilities (measured in km) would on average result in a 3.7% increase in the probability of choosing to cycle. 2. Intersection density and the link to node ratio of residential location were found to be positively associated with the choice of cycling to work
	Colombia				Neighborhood		SE/OT	No	

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
23 Cervero et al. (2009)		830 adults aged over 18 years who reported that they know how to ride a bike in Bogota	Cadaster Department of the City of Bogota using Geographic Information Systems (GIS) tools.	1. Dwelling units per hectare; 2. % of land area occupied by buildings; 3. Average building floor height; 4. Plot ratio (building m2 = land m2) 5. Entropy index of land-use mix (0–1 scale); 6. Proportion of buildings vertically mixed; 7. Proportion of total floor space in buildings with 2 + uses; 8. Public park area as % of total land area; 9. Average park size (hectares); 10. % of road links with median strips; 11. Traffic light density (traffic lights/street length); 12. Tree density (trees/street length); 13. Average lot size (m2); 14. Quadrilateral lots as % of total; 15. Percent of blocks with contained housing and access control; 16. Street density (street area/land area); 17. Proportion of intersections with: 1 point (cul de sac), 3 points, 4 points, 5 + points; 18. Bike-lane density 19. Route directness 20. Connectivity index (intersection nodes/street links); 21. Number of bridges; 22. Ciclovia two-way length (lineal meters);		Time duration of cycling for transport per day			1. High street densities (ie. road km/land area km > 0.20) will increase nearly twice as likely to cycle for utilitarian purposes 30 min or more per weekday. 2. Steep topography also deters cycling.

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
				23. Number of pedestrian bridges; 24. Pedestrian accidents per year; 25. Average automobile speeds on main streets; 26. Deaths (all types) in traffic accidents per year; 27. Number of reported crimes per year; 28. Number of: public schools; hospitals; public libraries; shopping centers (> 500m2); churches; banks; 29. Number of Trans Milenio (BRT) stations; 30. Shortest network distance to closest Trans Milenio station; 31. Number of feeder Trans Milenio stations					
24 Christiansen et al. (2016)	Adelaide, Australia (AUS); Ghent, Belgium (BEL); Curitiba, Brazil (BRA); Bogota, Colombia (COL); Olomouc, Czech Republic (CZ); Aarhus, Denmark (DEN); Cuernavaca, Mexico (MEX), Christchurch, North Shore, Waitakere, and Wellington, New Zealand (NZ), Stoke-on-Trent, United Kingdom (UK) and Baltimore and Seattle, United States (US)	12,181 adults aged 18–66 years from 14 cities	GIS	1. Net residential density (number of dwellings per km2 of buffer areas devoted to residential use), 2. Land-use mix (entropy score of three land-uses: residential, retail and civic) 3. Street connectivity (number of intersections with three or more intersecting road segments per km2) 4. Parks (number of parks intersecting participant buffers).	City	1. The frequency of cycling for transport. 2. The number of days of cycling during the last seven days (at least 10 min)	SE	Yes	1. Net residential density, intersection density, and land use mix were positively associated with the odds of engaging in any bouts (> 10 min) of cycling for transport in the last week; 2. Only intersection density and land use mix remained significantly associated in the multi-environment-variable models. 3. Land use mix were linearly positively associated with days per week of cycling for transport.

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
									4. The number of parks (1 park/km2; 500 m buffer) were positively associated with the odds of any cycling for transport in Ghent (BEL), Aarhus (DEN) and Seattle (USA) only
25 Snizek et al. (2013)	Denmark	398 cycling routes in Copenhagen and Frederiksberg	GIS	1. Roads with cycle facilities. 2. Distance to nearest cycle rack. 3. Number of cycle racks within 100 m. 4. Distance to the nearest traffic lights. 5. Street types 6. Distance to the closest group of bus stops. 7. Distance to nearest intersection. 8. Distance to town hall. 9. Number of companies within a distance of 100 m to the experience point 10. Number of retail units within a distance of 100 m to the experience point. 11. Distance to closest water or green area. 12. Percentage of green of route segments. 13. Deviations from the direct line. 14. The angle between the current segment and the line from the experience point towards town hall.	Individual respondent	Positive and negative cycling point	OT	No	1. Positive cycling experiences clearly related to the presence of en-route cycling facilities, and attractive nature environments within a short distance of large water bodies or green edges along the route. 2. Negative experiences are related to bus stops, high traffic densities along the route, as well as signaled and non- signaled intersections
26 Winters et al. (2010)	Canada	1402 current and potential cyclists aged above 18 from Metro Vancouver	1. TransLink 2. The regional transportation authority, 3. Bicycle coordinators from the	1. Vehicles; 2. Lane markings; 3. Intersections; 4. Distances, hills and connections;	Neighborhood	Cycling intent	OT	No	1. The strongest motivators were routes that were away from traffic, aesthetically pleasing, and easy to cycle.

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
			participating municipalities 4. Members of cycling advocacy groups	5. Road surfaces and maintenance; 6. Aesthetics and access; 7. Coordination with transit; 8. Safety					2. The strongest deterrents were unsafe surfaces and interactions with motor vehicles.
27 Van Dyck et al. (2010)	Belgium	1166 participants aged 20–65 years from 24 neighborhoods in Ghent	Service for Environmental Planning in Ghent, GIS	1. Walkability index conducted by residential density, 2. Intersection density 3. Land use mix	Neighborhood	Number of days and time duration (hours and minutes per day) of cycling for transport in last 7 days	SE	No	Living in a high-walkable neighborhood wassassociated with significantly more cycling for transport.
28 Piatkowski and Marshall (2015)	America	2030 paticipants in Denver	GIS, survey	in a 20 feet buffer, 1. One-way trip distance (self-report) 2. Origin link-to-node ratio 3. Origin intersection density 4. Destination link-to-node ratio 5. Destination intersection density 6. Same Origin and Destination. 7. Too few bike lanes; 8. Lack of connections between bike lanes and paths; 9. Worries about road safety (with regard to traffic); 10. Street conditions (potholes, cracks, bike lanes, etc); 11. Not enough light on existing bicycle facilities at night.	Neighborhood	Cycling intent	SE	No	one-way trip distance is significantly negatively associated with both the decision to begin commute-cycling as well as the decision to commute by bike with greater frequency.

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
29 Cole-Hunter et al. (2015)	Spain	769 adults aged above 18 years in Barcelona	GIS	in a 400 m buffer of home and Work/study, 1. Bicycle racks 2. Public bicycle stations 3. Public transport stations 4. Bicycle lane (%) 5. Greenness, NDVI 6. Elevation	Individual respondent	1. Cycling intent 2. Cycling frequency	SE	No	1. Significant positive determinants of propensity for bicycle commuting were the quantity of public bicycle stations within the home area, and amount of greenness within the work/study area; 2. The quantity of public trans- port stations within the home area and the mean elevation of the work/study area were significant negative determinants of the same propensity.
30 Mertens et al. (2016)	Belgium, the Netherlands, Hungary, France, UK	4612 adults from five European regions, Ghent region (Belgium), Randstad region (the Netherlands), Buda- pest (Hungary), Paris region (France) and Greater London (UK)	Assessing Levels of Physical Activity environmental questionnaire	In a five-point Likert scale: 1. There are special lanes, routes or paths for cycling in my neighborhood; 2. There is heavy traffic in my neighborhood related to cycling; 3. The cycles paths in my neighborhood are well maintained; 4. My neighborhood is a pleasant area for walking or cycling; 5. My neighborhood is generally free from litter, waste or graffiti; 6. The air in my neighborhood is polluted; 7. The speed of traffic in my neighborhood is usually low; 8. The level of crime in my neighborhood is high and 9. I have a choice of different routes for	Neighborhood	number of days and duration (average time per day) of cycling for transport in last 7 days	SE/OT	No	1. Low perceived traffic speed, high perceived choice between different routes to walk/cycle and high perceived air pollution in the neighbourhood were positively associated with the odds of engaging in cycling for transport. 2. Perceived pleasantness of the environment in relation to walking or cycling as well as perceived less air pollution were negatively associated with minutes per week cycling for transport among those who indicated to have cycled in the last seven days.

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
				walking or cycling in my neighborhood.					
31 Delfien Van Dyck et al. (2012)	America, Australia, Belgium	6014 adults aged 20–65 years from the USA (Baltimore and Seattle), Australia (Adelaide) and Belgium (Ghent)	the Dutch and English versions of the previously validated Neighborhood Environmental Walkability Scale (NEWS)	1. Residential density 2. Land use mix diversity – proximity of destinations 3. Land use mix diversity - # destinations within 20min walk 4. Land use mix access 5. Not many cul-de-sacs 6. Parking difficult near local shopping area 7. Not many barriers in neighborhood 8. Street connectivity 9. Proximity to transit stop 10. Walking and cycling facilities	Neighborhood	Number of days and duration (average time per day) of cycling for transport in last 7 days	SE/OT	No	Proximity to destinations, good walking and cycling facilities, perceiving difficulties in parking near local shopping areas, and perceived aesthetics were included in a 'cyclability' index. This index was linearly positively related to transport-related cycling and no gender- or country-differences were observed.
32 Kerr et al. (2016)	Australia, Belgium, Brazil, China, Colombia, Czech Republic, Denmark, Mexico, New Zealand, Spain, the United Kingdom, the United States	13,745 adults aged 18–65 years from 17cities in 12 countries, including Australia (AUS): Adelaide; Belgium (BEL): Ghent; Brazil (BR): Curitiba; China (CN): Hong Kong; Colombia (COL): Bogota; Czech Republic (CZ): Olomouc and Hradec Kralove; Denmark (DEN): Aarhus; Mexico (MEX): Cuernavaca; New Zealand (NZ): North Shore, Waitakere, Wellington, and Christchurch; Spain (SP): Pamplona; the United Kingdom (UK): Stoke-on-Trent; and the United States (US): Seattle, Washington, and Baltimore, Maryland.	Neighborhood Environment Walkability Scale–Abbreviated (NEWS–A): IPEN Subscales and Items	1. How common are detached single-family residences/ Townhouses or rows of 1–3-story houses/ Apartments or condos with 1–3 stories/ Apartments or condos with 4–6 stories/ Apartments or condos with 7–12 stories/ Apartments or condos with > 12 stories/ Apartments or condos with > 20 stories 2. Stores are within easy walking distance of my home. 3. There are many places to go within easy walking distance of my home. 4. It is easy to walk to a transit stop (bus, train) from my home. 5. The distance between intersections in my	City	1. Share of cycling for transport population, 2. Duration time of cycling for transport in last 7 days	SE	Yes	1. A significant non-linear association between perceived residential density and any cycling for transport that was consistently negative in slope; 2. Any cycling for transport was significantly related to perceived land use mix–access, street connectivity, infrastructure, aesthetics, safety, and perceived distance to destinations.

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
				neighborhood is usually short 6. There are many alternative routes for getting from place to place in my neighborhood 7. There are sidewalks on most of the streets in my neighborhood. 8. My neighborhood streets are well lit at night. 9. Walkers and bikers on the streets in my neighborhood can be easily seen by people in their homes. 10. There are crosswalks and pedestrian signals to help walkers cross busy streets in my neighborhood. 11. There are trees along the streets in my neighborhood. 12. There are many interesting things to look at while walking in my neighborhood. 13. There are many attractive natural sights in my neighborhood (such as landscaping, views). 14 There are attractive buildings/homes in my neighborhood. There is so much traffic along nearby streets that it makes it difficult or unpleasant to walk in my neighborhood. 15. The speed of traffic on the street I live on is					

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
				usually slow (30 mph/50 kph or less). 16. Most drivers exceed the posted speed limits while driving in my neighborhood. There is a high crime rate in my neighborhood. 17. The crime rate in my neighborhood makes it unsafe to go on walks during the day. 18. The crime rate in my neighborhood makes it unsafe to go on walks at night. 19. About how long would it take to walk from your home to the nearest Supermarket/Other food/grocery, small grocery/convenience, fruit/veg market, bakery, butcher shop/Post office/Any school, elementary, other, nursery/Transit stop/Any restaurant, fast food, non–fast food, café/coffee place/Park/other public open space/Gym/fitness facility, recreation center, swimming pool/Library/Video store/Drug store/pharmacy/Bookstore/Other shops and services					
33 Van Cauwenberg et al. (2012)	Belgium	48,879 Flemish adults aged above 65 within 135 municipalities collected in 2004–2010	survey, the Study Service of the Flemish Government	1. Short distances to services; 2. Number of shops 3. Access to Public transport	Neighborhood	Frequency of cycling for transportation	SE/OT	No	1. Number of shops, satisfaction with public transport was positively related to daily cycling for transportation.

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
				4. Presence of public toilets 5. Presence of benches 6. Presence of crossings 7. Condition of sidewalks 8. Absence of high ramps 9. Traffic safety 10. Feelings of unsafety 11. Street lighting 12. Absence of decay 13. Absence of noise 14. Greenery 15. Public transportation subscriptions (% of older adults)					2. Feelings of unsafety were related to a decreased likely-hood of daily cycling for transportation in females but not in males. 3. Traffic safety was negatively related to daily cycling for transportation.
34 Badland et al. (2013)	Australia	909 adults whom moving into 74 newhousing developments in Perth in 2003–2004	1. Survey 2. Objective environmental data, 3. GIS	Percieved: 1. Lots of greenery in the neighborhood 2. Interesting features in the neighborhood 3. Attractive buildings and homes in the neighborhood 4. Pleasant natural features in the neighborhood 5. Presence of walking and cycling paths in the neighborhood 6. Neighborhood is near busy roads 7. Traffic speeds are slow on nearby streets 8. Many traffic slowing devices in the neighborhood 9. Neighborhood streets do not have many culs-de-sac 10. Neighborhood has many four-way intersections 11. Many alternative routes in the neighborhood Objective:	Neighborhood	Frequency of cycling for recreation and transport per week	SE	Yes	1. Respondents who perceived they lived near busy streets were half as likely to start cycling for recreation than those living on quieter roads. 2. Respondents living in higher walkable neighborhoods (recreation) or with higher street connectivity (as measured by GIS) were more likely to start cycling for recreation when compared with their reference groups. 3. No significant relationships between objective measures of the neighborhood and uptake of cycling for transport.

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
				12. Street connectivity z-score (median split) 13. Residential density z-score (median split) 14. Land use mix (recreation) z-score (median split) 15. Land use mix (transport) z-score (median split) 16. Walkability index (recreation) z-score (median split) 17. Walkability index (transport) z-score (median split) 18. Cyclable road ratio (median split) 19. Cycle path length within 1600 m service area (median split)					
35 Beenackers et al. (2012)	Australia	1289 adults whom moving into 74 new housing developments in Perth in 2003–2004	1. Neighborhood Environment Walkability Scale 2. GIS	in a 1600 m buffer: 1. Connectivity, 2. Residential density, 3. Land-use mix, 4. Number of destinations relevant for transport or recreation 5. Access to mixed services—scale 6. Neighborhood aesthetics—scale 7. Traffic hazards—scale 8. Major barriers present 9. Local parking is difficult 10. Access to park 11. Access to cycling paths 12. Pedestrian crossings present 13. Number of transport destinations 14. Number of recreation destinations	Neighborhood	Duration time (mins) of cycling for transport and cycling for recreation	SE	Yes	1. That greater objective residential density, increased access to a park, and more recreation-related destinations were positively associated with an increase in transport-related cycling after relocation. 2. A decrease in objective connectivity, increased access to services, and more pedestrian crossings were marginally associated with the uptake of transport-related cycling. 3. An increase in objective connectivity was associated with the uptake of recreational cycling.

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
36 Maki-Opas, de Munter, Maas, den Hertog, and Kunst (2014)	Netherlands	697 children aged 10–18 years in Amsterdam	Statistics Netherlands and the Department for Research and Statistics at the Municipality of Amsterdam 2. GIS 3. NEWS questionnaire survey	1. There are many attractive natural sights in my neighborhood (e.g. landscape, views), 2. My neighborhood is generally free of litter, 3. It is safe to cycle in or near my neighborhood, 4. There are cycling paths in or near my neighborhood 5. There are many major intersections in my neighborhood. 6. The percentage of green area within a radius of 500 m around the residence. 7. The Euclidean distance between school and home	Neighborhood	1. Average number of days, 2. Duration time (mins) of cycling to and from school per week	SE/OT	No	1. For every unit of increase in the bicycle-friendly infrastructure, there was a 21% increase in the odds for cycling to and from school (bicycle-friendly infrastructure includes, cycle paths in my neighborhood, traffic is slow, streets are well lit and there are pedestrian crossings and traffic lights, the traffic intensity.
37 Zhao (2013)	China	613 household heads of 613 households in Beijing from 60 communities.	Survey	1. Residents per hectare in built-up area (at the sub-district level) (100 persons/ha) 2. Jobs per hectare in built-up area (at the sub-district level) (100 jobs/ha) 3. A jobs–housing balance index measured at the sub- district level 4. Distance to the old city center (Tiananmen square) from the centroid of community (km) 5. One-way commuting time (minutes) 6. A diversity index measured by entropy method 7. Length of local streets per square km in	Neighborhood	Share of cycling for commuting	SE	No	Higher destination accessibility, a higher number of exclusive bicycle lanes, a mixed environment and greater connectivity between local streets tend to increase the use of the bicycle.

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
				built-up area within the local impact range (km/square km) 8. Number of crossings of streets within the local impact range (unit) 9. Length of main road and expressways per km in built-up area within the local impact range (km/square km) 10. Number of crossings of main road and expressways within the local impact range (unit) 11. Length of bicycle lanes separated from motorized traffic per km in built-up area within the local impact range (km) 12. Distance to closest metro station from the centroid of community (km)					
38 Ma et al. (2014)	America	830 responses in three neighborhoods in Portland	the Regional Land Information System (RLIS) from Portland Metro, Reference USA,	1. Total miles of striped bike lanes, multi-use path and low-traffic through streets within one mile of home. 2. Number of street intersections with three or more valences divided by total number of intersections within one mile of home 3. Number of business establishments within one mile of home (bank, restaurant, library, post office, grocery store, pharmacy, bars, bookstore, convenient store,	Neighborhood	Frequency of cycling	SE	No	1. A neighborhood with connected streets, nearby business establishments, and low-traffic streets could make residents feel that bicycling in the neighborhood is easy and safe, with nearby destinations. 2. Perceptions of the environment have a significant positive association with bicycling behavior, indicating that residents who perceive their neighborhood as bikeable

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Table A.1 (*continued*)

Author	Country	Sample	Built environment factors data source	Built environment factors	Analyzed geographic units	Cycling metrics	Controls[1]	Self-selection controlled	Results
				fitness center, theater, and church) 4. Ratio of area with a slope less than 25% within one mile of home. 5. For me to ride a bicycle for daily travel from home would be easy 6. I know where safe bike routes are in my neighborhood 7. Many of the places I need to get to regularly are within bicycling distance of my home					actually bicycle more often.
39 Verhoeven et al. (2017)	Belgium	882 adolescents aged 12–16 years from Flanders	Survey from panoramic color photographs	1. Separation of cycle path 2. Evenness of cycle path 3. Speed limit 4. Speed bump 5. Traffic density 6. Amount of vegetation 7. Maintenance	Individual respondent	1. Cycling routes choice 2. Number of days per week and average daily duration time of cycling to various destinations within the last 7 days	SE	Yes	1. Adolescents' preference to cycle for transport was predominantly determined by separation of cycle path, followed by shorter cycling distance and co-participation in cycling. 2. Higher preferences were observed for a separation between the cycle path and motorized traffic by means of a hedge versus a curb, versus a marked line

[1]. AT = Attitudinal variables.
SE = Socioeconomic variables.
WE = Weather variables.
LE = Level of service variables.
ST = Station variables.
OT = Other variables.

Table A.2
Characterization of studies by the environmental factors measured method, the environmental scale, the type(s) of cycling.

Study No.	Environment attributes measured		Environmental attributes scale			Cycling type			
	Objective	Perceived	Micro	Meso	Macro	Transport	Commuting	Recreation	General
1		X	X						X
2		X	X			X			
3		X		X		X		X	
4	X	X	X			X	X		
5	X	X		X		X			
6	X			X	X		X		
7	X		X			X			
8	X		X						X
9	X			X		X			
10	X			X		X			
11		X		X		X	X		
12		X		X		X		X	
13		X		X		X		X	
14	X			X		X		X	
15	X		X						X
16	X				X		X		
17	X		X			X		X	
18	X	X		X					X
19	X		X						X
20		X	X			X			
21	X		X					X	
22	X			X			X		X
23	X			X		X			
24	X				X	X			X
25		X	X						X
26		X	X						X
27	X			X		X			
28	X	X	X				X		
29	X		X				X		
30		X		X		X			
31		X		X		X			
32		X			X	X			
33	X	X		X		X			
34	X	X		X		X		X	
35	X	X	X			X		X	
36	X	X		X			X		
37	X			X			X		
38	X	X		X					X
39		X	X			X			
Total	26	22	16	20	4	23	9	8	10

Appendix B

Table B.1
Elasticity of cycling for transportation with respect to density.

Study No.	Model	N	Y	X	e
9	Multilevel logistic regression	3280	Bike mode choice	Population per hectare	0.043096
4	Binary logistic model	902	Bike mode choice for utilitarian trips	# Retail jobs within 1/2-mile buffer	−0.01242
4	Multivariate linear model	902	Days of utilitarian bicycling	# Retail jobs within 1/2-milebuffer	0.031091
17	Bivariate and multivariate logistic regression	573	bike mode choice	Built coverage (built cover/built lots)	−0.05184

Table B.2
Elasticity of cycling for transportation with respect to land use mix

Study No.	Model	N	Y	X	e
7	logistic regression model	1206	bike trips per person	land use mix entropy	0.139216
7	logistic regression model	1206	bike trips per person	land use mix entropy	−0.42601
9	Multilevel logistic regression	3280	bike mode choice	land use mix entropy	0.026836

Table B.3
Elasticity of cycling for transportation with respect to accessibility of non-residential destination

Study No.	Model	N	Y	X	e
33	Logistic regression	48879	bike trips per person	Number of shops	0.222033

Table B.4
Elasticity of cycling for transportation with respect to street/route connectivity

Study No.	Model	N	Y	X	e
9	Multilevel logistic regression	3280	bike mode choice	route intersection density (# intersections/ha)	0.147944
9	Multilevel logistic regression	3280	bike mode choice	origin intersection density (# intersections/ha)	0.055049
9	Multilevel logistic regression	3280	bike mode choice	destination intersection density (# intersections/ha)	0.110098
7	logistic regression model	1206	bike trips per person	Street density	0.009799

Table B.5
Elasticity of cycling for transportation with respect to open space /green space

Study No.	Model	N	Y	X	e
10	Logistic model	6037	bike trips per person	Presence of trees	0.116358

Table B.6
Elasticity of cycling for transportation with respect to aesthetics/attractiveness

Study No.	Model	N	Y	X	e
30	Logistic regression	4612	bike trips per person	Pleasant environment to cycle	0

Table B.7
Elasticity of cycling for transportation with respect to cycling facilities/cycling paths

Study No.	Model	N	Y	X	e
9	Multilevel logistic regression	3280	bike mode choice	% road network: designated bike route	0.059012
10	Logistic model	6037	bike trips per person	bicycle lanes	−0.00877
4	binary logistic model	902	bike mode choice for utilitarian trips	Miles of bike lane (GIS)	0.169551
4	multivariate linear model	902	Days of utilitarian bicycling	Miles of off-street bike path (GIS)	−0.04877
30	Logistic regression	4612	bike trips per person	Presence of cycle paths	0.20268

Table B.8
Elasticity of cycling for transportation with respect to cycling safety

Study No.	Model	N	Y	X	e
7	logistic regression model	1206	bike trips per person	Traffic safety number	0.14916
9	Multilevel logistic regression	3280	bike mode choice	Presence of traffic calming features	0.223636
10	Logistic model	6037	bike trips per person	Traffic calming features	−1.43988
10	Logistic model	6037	bike trips per person	Speed limit ≤30 km/h	0.854931
30	Logistic regression	4612	bike trips per person	Low traffic speed	0.279973
4	binary logistic model	902	bike mode choice for utilitarian trips	Perceived there are off-street bike paths	0.166457

Table B.9
Elasticity of cycling for commuting with respect to street/route connectivity

Study No.	Model	N	Y	X	e
37	multinomial logit model	613	bike mode choice	Connections of local streets	1.043938
28	Binary and Ordered Logistic Regression	2030	bike mode choice	Origin intersection density	0.121523
28	Binary and Ordered Logistic Regression	2030	bike mode choice	Destination intersection density	0

Table B.10
Elasticity of cycling for commuting with respect to cycling facilities/cycling paths

Study No.	Model	N	Y	X	e
16	Multiple regression	90 of the 100 largest U.S. cities	Bike commuters	bike lanes per 100,000 population	0.25
16	Multiple regression	90 of the 100 largest U.S. cities	Bike commuters	bike paths per 100,000 population	0.091
37	multinomial logit model	613	bike mode choice	Exclusive bicycle lanes	0.518724

Table B.11
Elasticity of cycling for general with respect to open space/green space

Study No.	Model	N	Y	X	e
8	GLMM model	2687	count of bicycle	Pct. of water body in 1-mile buffer	0.32
8	GLMM model	2687	count of bicycle	Pct. of water body in 0.5-mile buffer	0.22
8	GLMM model	2687	count of bicycle	Pct. of water body in 0.25-mile buffer	0.27

Table B.12
Elasticity of cycling for general with respect to low slope

Study No.	Model	N	Y	X	e
8	GLMM model	2687	count of bicycle	Pct. of steep area in 1-mile buffer	−0.71
8	GLMM model	2687	count of bicycle	Pct. of steep area in 0.5-mile buffer	−0.02
8	GLMM model	2687	count of bicycle	Pct. of steep area in 0.25-mile buffer	−0.05

Table B.13
Elasticity of cycling for general with respect to cycling facilities/cycling paths

Study No.	Model	N	y	x	e
8	GLMM model	2687	count of bicycle	Bike lane in 1-mile buffer	0.88
8	GLMM model	2687	count of bicycle	Bike lane in 0.5-mile buffer	0.56
8	GLMM model	2687	count of bicycle	Bike lane in 0.25-mile buffer	0.59

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