The Built Environment as a Determinant of Physical Activity: A Systematic Review of Longitudinal Studies and Natural Experiments

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Abstract

Background

Physical inactivity is a global problem that increases the risk of many chronic diseases and shortens life expectancy. The built environment contributes to physical inactivity through accessibility of amenities and transportation patterns. With better urban planning, cities could be designed to enhance active transportation and population health on a permanent basis.

Purpose

We conducted a systematic review to identify determinants of the built environment associated with physical activity and to evaluate how changes in the built environment are associated with changes in physical activity.

Methods

We searched six databases, from the inception of each until December 2015, for studies that were written in English, used longitudinal before-and-after design and assessed changes in both the built environment and physical activity. A total of 21 prospective cohort studies and 30 natural experiments were included in the review.

Results

The review showed that changes in the built environment and in physical activity were related. A higher objective accessibility and new infrastructure for walking, cycling and public transportation were associated with increased overall and transportation-related physical activity. Some evidence was found for perceived aesthetics and safety as determinants of physical activity.

Conclusions

Improved objectively measured accessibility of different type of destinations and public transportation and land use mix were associated with increased physical activity. Creating new infrastructure for walking, cycling and public transportation could induce demand for walking and cycling. The results support the creation of compact and diverse residential areas and investments into infrastructure that encourage active modes of transportation.

Key words: evidence synthesis, urban form, physical activity, active transportation, causal inference

Introduction

Physical inactivity is associated with many chronic diseases and early deaths. It was estimated to cost international $ 67.5 billion worldwide through health care costs and productivity losses in 2013 (1). Land use and transportation policies have been recognized as major contributors to physical inactivity around the world. Thus, designing cities to support active transportation is a feasible strategy for enhancing physical activity and population health on a permanent basis (2).

The recent *Lancet* series on urban design, transport and health identified eight integrated regional and local interventions to enhance active transportation and reduce private motor vehicle use: *destination accessibility, employment distribution, parking policies, pedestrian- and cycling-friendly street networks, residential density, public transportation availability, mixed land use* and *desirability of active travel modes* (3). Moreover, compact cities that encompass these features experience health gains in terms of diabetes, cardiovascular disease and respiratory disease (4).

To develop healthy communities and effective environmental interventions for promoting physical activity, it is important to gather robust knowledge of the most essential modifiable factors of the built environment that activate people. During the past 15 years, the environmental determinants of physical activity have been mainly studied in cross-sectional settings. Few longitudinal studies have examined causality (5,6).

The number of longitudinal studies assessing the effect of changes in the built environment on physical activity has multiplied during the last five years. The rapidly growing evidence base regarding the environmental determinants of physical activity must be regularly updated and reviewed with systematic methodology (7). The objectives of the present systematic literature review were 1) to identify determinants of the built environment associated with physical activity and 2) to evaluate how changes in the built environment are associated with changes in physical activity.

Methods

The review follows the guidelines of the PRISMA statement (8). The protocol was registered to the international prospective register of systematic reviews (PROSPERO) on 30 January 2016 (registration number: CRD42016033646).

Eligibility criteria

We included studies utilizing longitudinal before-and-after design (i.e., prospective longitudinal cohort studies and natural experiments with at least two data collection points). Still, natural experiments with before-and-after cross-sectional data (with different individuals) were also included. To be eligible, a study had to assess changes in the built environment and physical activity between baseline and follow-up.

Participants representing the general population, without age restriction, were eligible. We excluded studies on institutionalized individuals or on subjects not able to perform habitual physical activities.

A change in the built environment was used as the main exposure. We included both perceived and objective Geographic Information System (GIS)-based measures of the built environment since previous studies have shown discrepancies between their potential effects on physical activity (5). Of interest were prospective longitudinal cohort studies assessing residential relocation and natural experiments focusing on changes in the built environment. Hence, a change in the built environment had to be assessed in terms of moving from one kind of environment into another or improvements in neighborhood- or town-level infrastructure (i.e., creating new walking or cycling trails). Also, studies in which changes in the built environment were assessed with subjective perceptions and studies that used micro-environment interventions (i.e., park improvements) were included. Studies that measured the built environment inside homes, workplaces or schools or studies that focused solely on neighborhood socioeconomic status were excluded.

We used a change in physical activity as the primary outcome, including self-reported or objectively measured 1) overall physical activity, 2) transportation-related physical activity and 3) leisure time physical activity. For inclusion, we accepted studies using a variety of outcome measures, such as walking, cycling, jogging, exercise, moderate to vigorous physical activity, travel mode, share or number of trips, travel behavior, number of cyclists and number of visitors. We also included studies in which the change in physical activity was reported, even if it was not the primary outcome measure. We included only studies written in English and published in scientific peer-reviewed journals.

Information sources

We searched six electronic databases: Medline, PubMed, Scopus, Web of Science, Transportation Research Information Services and the Active Living Research database. In addition, we screened reference lists from previous reviews and other relevant publications to find additional studies.

The Medline search strategy (see Electronic Supplementary Figure S1) was developed in cooperation with a health science librarian using medical subject headings and adapted for other databases using free word searches. Key search terms for physical activity were these: physical activity, active transportation, walking, bicycling, motor activity and exercise. The search terms covered active modes of transportation because physical activity was our main outcome. However, in Medline also transportation was included as a medical subject heading which encompassed active transportation.

For the built environment, the terms included neighborhood, physical environment, built environment, walkability, environment design, environment and cities. For study design, the terms were longitudinal studies, cohort studies, follow-up studies, natural experiments, causality, residential relocation and neighborhood self-selection. The searches were carried out for studies published from each database's inception until 11 December 2015.

The initial literature search produced 4335 articles (Figure 1). In addition, we identified 35 publications by screening reference lists from previous reviews and other relevant publications. Based on titles and abstracts, we excluded 4101 studies that were out of this review's scope. Then duplicates were removed. The initial search and title and abstract screening were managed by MK. Full text papers (n = 111) were screened by at least three review authors (MK, TL and either RK or TI) for final inclusion, using a predefined inclusion form containing the eligibility criteria. Disagreements were resolved by discussion. Finally, 51 studies were found to be eligible for this review. The review's authors were not blinded to the studies' authors or institutions.

Data from all of the included studies (n = 51) were extracted into a predefined data extraction document by MK, with verification by RK, TL and TI, in order to reduce bias and error. Extraction included the following items: methods (objective, study design, outcome measures, covariates, statistical analysis and residential self-selection adjustment); participants (country, setting, population, number, age, gender, subject selection, control group assessment and response rates); exposures (experiment description if applicable, built environment measures and follow-up time and frequency); and main results (changes in physical activity).

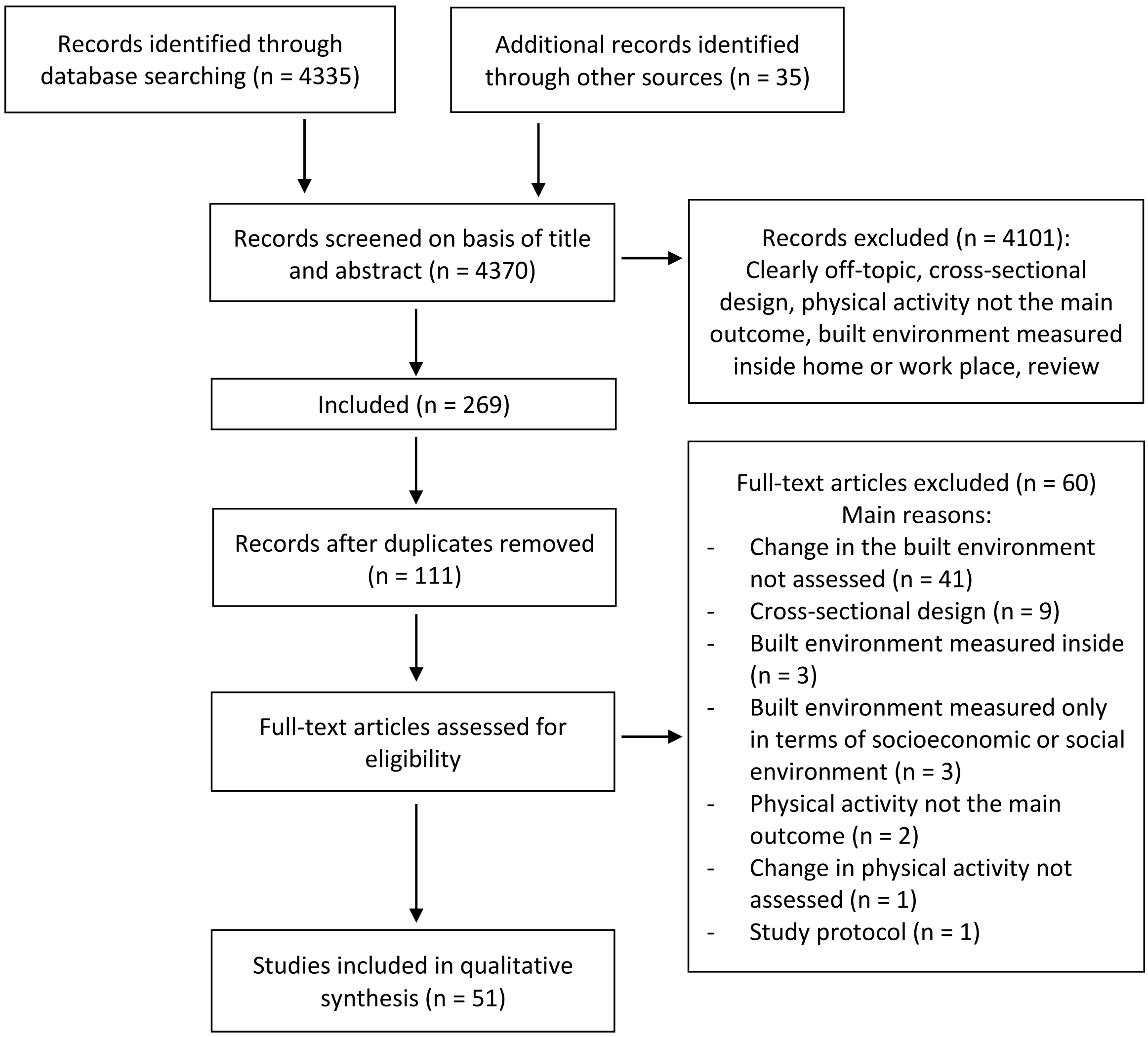

Figure 1. PRISMA flow diagram of the study selection process

Risk of bias in individual studies

We assessed the risk of bias at the study level with the QualSyst tool developed by the Alberta Heritage Foundation for Medical Research (9). It was selected because it enabled us to evaluate studies with the two different designs included in the present review.

The risk of bias was evaluated with its summary score (range: 0–1), with a higher score indicating better quality. The tool contains 14 criteria, including objective, study design, method of subject/comparison group selection, subject characteristics, intervention allocation, blinding, outcome measure definition, exposure measure definition, sample size, analytic methods, estimate of variance, control for confounding, reporting results and conclusions. All items were scored depending on the degree to which the specific criteria were met ("yes" = 2, "partial" = 1, "no" = 0). Items not applicable to a particular study design were marked "N/A" and excluded from the summary score. We adjusted the tool for the longitudinal study designs included in the review. Hence, follow-up and exposure time to the experiment, sample representativeness over time, response rate and loss to follow-up and residential self-selection adjustments were evaluated as part of the 14 criteria presented before. In terms of natural experiments, we also evaluated use of control groups and their similarity to intervention groups.

To ascertain the validity of the tool, the review authors (MK, RK, TI and TL) independently evaluated five randomly selected research papers (10%) from categories representing two prospective longitudinal cohort studies, two natural experiments and one park improvement study. Disagreements concerning the items and evaluation were resolved by discussion. Based on validation of the tool, MK evaluated the remaining research papers, with verification by the other review authors.

Synthesis of results

We used the association between changes in the built environment and changes in physical activity as the primary measure of effect. To eliminate potential bias due to confounding, only adjusted effect estimates were utilized in the analyses. We chose narrative synthesis as a method due to the heterogeneity of studies and the variety of exposure and outcome measures, which prevented quantitative meta-analysis.

The Figures 2 and 3 displaying the results were prepared according to the number of associations coded as positively significant ("+"), negatively significant ("-") or having no association ("0"). Associations with p-value ≤ 0.05 were considered statistically significant. The number of associations in the figures refer to the sum of all the associations obtained from different studies. In a specific category, multiple associations may arise from the same study if several variables that were combined in that category had been used, or different types of physical activity e.g. walking and cycling were assessed separately. Data synthesis was stratified by the built environment measurement mode and domain of physical activity.

We combined different exposure measures of the objectively measured built environment as follows: new infrastructure for walking, cycling and public transportation; accessibility of destinations and public transportation and land use mix; park and playground improvements; street network characteristics; population density; and aggregate walkability measures. Perceived built environment measures were combined into the categories of accessibility, aesthetics, safety, convenience, barriers, and street network characteristics.

The development of the built environment categories was an inductive process derived empirically from the studies. First, all measures were combined into a single table stratified by objective or self-reported measurement mode. Then, we thematically combined similar measures and created the categories which were labelled to represent all the individual measures included. Individual measures included in the different categories are presented in parentheses in Figures 2 and 3. Physical activity was stratified by domain (overall, transport and leisure time physical activity) as suggested in a recent paper concerning improving current practice in reviews of the built environment and physical activity (7). All reported associations in the text are statistically significant.

Results

Study characteristics

Of the eligible 51 studies, 20 studies were prospective longitudinal cohort studies, and 31 were natural experiments. The number of individuals followed-up upon in individual studies ranged from 32 to 1,300,000. Average follow-up time was 3.7 years, ranging from one month to 15 years. The study population consisted of adults in 35 studies, children and adolescents in six studies and elderly people in two studies; eight studies did not use age restrictions. All of the studies were conducted from 2003 to 2015. All were conducted in high-income economies (28 in North America, 11 in Europe, nine in Australia, two in Asia and one in New Zealand). The setting was urban in 38 studies, suburban or rural in six and not stated in seven.

Physical activity was measured objectively (e.g., with accelerometers) in five studies and with systematic observations in nine studies. Self-reported physical activity was used in 34 studies. Three studies used both self-reported and objectively measured physical activity. The built environment was measured objectively (with GIS) in 24 studies, the perceived built environment was used in 10 studies and a combination was used in six studies. Construction of new infrastructure was used as the only measure of the built environment in 11 studies. For comprehensive study characteristics, effect sizes and 95% confidence intervals, see Electronic Supplementary Table S1.

Quality of the studies included in the review

The mean quality score in prospective longitudinal cohort studies was high (0.87 on average, range: 0.73–1.00). The main sources of bias were related to confounding, measurement and subject selection. Fifty-five percent of the studies used non-validated measures of physical activity or did not use time-varying measures of the built environment. In 40% of the studies, the sample was not population-representative, and there were high rates of loss to follow-up.

In natural experiments, the mean quality score was 0.78 (range: 0.59–0.91). All natural experiments suffered from poor sample representativeness or lack of a control group. Other major methodological limitations were related to confounding (65% of the studies), small sample sizes and response rates (58% of the studies) and short periods of exposure to the experiment (48% of the studies). Quality scores of the individual studies are presented in Electronic Supplementary Table S1.

Objective built environment measures

The overview of the findings related to the objectively measured built environment and its association with the different physical activity domains is presented in Figure 2.

Objective BE measures	PA domain (number of studies)	Number of associations obtained from different studies 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
New infrastructure for walking, cycling, and public transportation (routes for walking and cycling, rail infrastructure, bike parking, street improvements)	Overall PA (n=11)	S, 0,86[10] N=1465	S, 0,86[10] N=1465	S, 0,86[11] N=1510	O, 0,86[16] N=51	O, 0,80[13] N=N/A	O, 0,80[13] N=N/A	O, 0,80[13] N=N/A	S, 0,73[14] N=512	O, 0,73[17] N=51	S, 0,59[18] N=526	S, 0,82[63] N=366	S, 0,82[63] N=366	S, 0,82[64] N=498	O, 0,77[59] N=353	S, 0,73[60] N=36	S, 0,68[20] N=107	S, 0,68[20] N=107
	Transport PA (n=5)	S, 0,86[10] N=1465	S, 0,85[12] N=1300000	S, 0,85[12] N=1300000	S, 0,82[19] N=7410	S, 0,82[19] N=7410	S, 0,82[15] N=470	S, 0,86[10] N=1465	S, 0,82[63] N=366	S, 0,82[19] N=7410	S, 0,82[19] N=7410							
	Leisure time PA (n=4)	S, 0,86[16] N=51	S, 0,86[10] N=1465	S, 0,86[10] N=1465	S, 0,82[63] N=366	S, 0,82[64] N=498												
Accessibility (number of destinations, land-use mix, public transit availability, sport facility availability, distance to parks)	Overall PA (n=4)	S, 0,86[30] N=25834	O, 0,86[22] N=177	S, 0,68[29] N=169	S, 0,68[29] N=169	O, 0,86[22] N=177	O, 0,86[26] N=32											
	Transport PA (n=4)	S, 0,95[21] N=6027	S, 0,95[21] N=6027	S, 0,91[25] N=565	S, 0,91[25] N=565	S, 0,91[25] N=565	S, 0,86[31] N=20354	S, 0,82[24] N=1420	S, 0,77[32] N=?	S, 0,95[21] N=6027	S, 0,95[21] N=6027	S, 0,86[31] N=20354						
	Leisure time PA (n=4)	S, 1,00[28] N=12701	S, 0,95[27] N=6168	S, 0,82[24] N=1420	S, 0,95[21] N=6027	S, 0,95[21] N=6027	S, 0,95[21] N=6027	S, 0,95[21] N=6027	S, 0,86[31] N=20354	S, 0,86[31] N=20354	S, 0,86[31] N=20354	S, 0,86[39] N=1427						
Park and playground improvements (renovation, new equipment)	Overall PA (n=6)	O, 0,81[34] N=75	O, 0,77[35] N=633	O, 0,75[36] N=N/A	O, 0,70[33] N=N/A	O, 0,70[33] N=N/A	O, 0,65[37] N=N/A	O, 0,86[62] N=156										
	Transport PA																	
	Leisure time PA (n=1)	S, 0,68[61] N=620																
Street network characteristics (street connectivity, road characteristics)	Overall PA (n=4)	S, 0,95[38] N=5115	S, 0,95[38] N=5115	O, 0,86[26] N=32	S, 0,68[29] N=169	S, 0,95[38] N=5115	O, 0,86[26] N=32	S, 0,95[38] N=5115	O, 0,86[22] N=177									
	Transport PA (n=3)	S, 0,95[21] N=6027	S, 0,91[25] N=565	S, 0,86[31] N=20354	S, 0,86[31] N=20354	S, 0,86[39] N=1427												
	Leisure time PA (n=4)	S, 0,86[39] N=1427	S, 1,00[28] N=12701	S, 0,95[21] N=6027	S, 0,86[31] N=20354	S, 0,86[31] N=20354	S, 0,86[31] N=20354	S, 0,86[31] N=20354										
Density (population density, employment and service/job density)	Overall PA (n=3)	S, 0,68[29] N=169	O, 0,86[22] N=177	O, 0,86[26] N=32	O, 0,86[26] N=32	O, 0,86[26] N=33												
	Transport PA (n=4)	S, 0,86[31] N=20354	S, 0,86[39] N=1427	S, 0,77[32] N=?	S, 0,95[21] N=6027	S, 0,91[25] N=565	S, 0,77[32] N=?											
	Leisure time PA (n=3)	S, 0,86[31] N=20354	S, 0,95[21] N=6027	S, 0,86[39] N=1427	S, 0,86[31] N=20354													
Aggregate walkability measures (walkability index, walk score, sprawl index)	Overall PA (n=4)	O, 0,86[22] N=177	O, 0,91[56] N=518	S, 0,86[65] N=1047	S, 0,77[58] N=3448	S, 0,77[58] N=3448												
	Transport PA (n=3)	S, 0,95[41] N=2976	S, 0,91[40] N=701	S, 0,86[65] N=1047														
	Leisure time PA (n=2)	S, 0,91[40] N=701	S, 0,86[65] N=1047															
Other (coastal location, crime, landscape diversity)	Overall PA (n=1)	S, 0,77[42] N=800																
	Transport PA																	
	Leisure time PA (n=1)	S, 1,00[28] N=12701	S, 1,00[28] N=12701															

Statistically significant positive association

Null association

Statistically significant negative association

Figure 2. Number of associations between objective built environment (BE) measures and physical activity (PA). Characters in the cells: O = objectively measured physical activity, S = self-reported physical activity, Quality score[reference], N = Sample size.

New infrastructure for walking, cycling and public transportation

Of the sixteen natural experiments, a change in infrastructure was associated with increased physical activity in nine studies and decreased physical activity in one study. The average quality of these studies was moderate (quality score 0.78, range: 0.59–0.86). The strongest level of evidence was found for overall and transportation-related physical activity.

The majority of these studies assessed new routes for walking and cycling. Among British adults, living closer to new, high-quality, traffic-free routes for walking and cycling was associated with an increase in these activities by 15.3 min/week and total physical activity by 12.5 min/week for each kilometer closer to the new route a person lived. In addition, walking for transportation increased by 8.8 min (10). With the same population, the effect of proximity to the new routes on change in time spent walking and cycling was 90% explained by use of the new infrastructure implying causal inference (11).

Town-level cycling initiatives were associated with an increase from 5.8% to 6.8% in the prevalence of cycling and 1,71% increase in walking to work within 10 years among 1.3 million commuters (12). The initiatives included cycling to workplaces, schools and colleges, general infrastructure improvements, cycling to stations, and targeting specific neighborhoods or groups. In a US study, constructing a new greenway/trail was associated with on average eight more people walking and cycling in the experimental neighborhood during the two hour data collection period (13).

A new cycle path was associated with more cycling in the intervention area (24%) compared to control neighborhoods (7%) among Australian adults. The shorter the distance to the new path was, the higher was its use (14). Similar results were obtained in respect to proximity to a new busway with a parallel path for walking and cycling, which predicted 1.8 times higher likelihood for a large increase in active travel mode share compared to subjects living further away (15).

Three natural experiments found significant associations between new rail infrastructure and physical activity. In US, a new rail stop was associated with increased bouts of moderate activity and increased time spent in leisure walks (16,17). A new railway corridor was also associated with increased overall physical activity among households who valued transit-oriented development (18).

Moreover, 19 percentage point increase in transportation walking and 11 percentage point increase in transport cycling were found among children after providing bike parking infrastructure (19). There were also some contradictory findings related to new infrastructure. Installation of a new multi-use trail was associated with a decreased amount of walking and total activity (β = -0.26) in all other age groups except for adults, who increased their total physical activity (20).

Accessibility

Overall, improved accessibility was associated with increased physical activity in eight and decreased physical activity in one study. Accessibility was assessed according to number of destinations, land use mix, public transit availability, sport facility availability or distance to parks. The average quality score of the studies in this category was high (0.87, range: 0.68 – 1).

Increases in both social and walking destinations were associated with enhanced transportation walking by 3.53 and 3.33 min/week, respectively (21), and one unit increase in the number of daily destinations with 0.37 unit increase in overall physical activity among females (22). Among Australian adults, each objectively measured transportation-related destination was associated with an increase in walking for transportation by 5.8 min/week and each recreational destination with an increase in recreational walking by 17.6 min/week after relocation to a new housing development designed according to the Livable Neighborhoods Guidelines (23,24). Among the same study population, an increase in the total number of destinations and land use mix were related to more walking for transportation (25). Participants with access to more destinations types had 1.4 times higher odds for increased transport walking compared to those with poorer access. In terms of land use mix the odds were 1.33 times higher for participants with more diverse environment (25).

In US, moving to a new urbanist community predicted over 4000 fewer steps per day among women along with an increased land use mix (26). A greater increase in recreational facility density was associated with a less pronounced decline in recreational physical activity over time by 10.3 MET minutes/week (27); however, pay facility availability was associated with increased bouts of moderate to vigorous physical activity in male and public facility availability in female movers with relatively small effect sizes (0.024% and 0.053%, respectively) (28). In China, greater exposure to recreational areas on campus was associated with increased walking distances ($\beta = 0.147$) among university students (29). In Finland, moving to an area with poor access to sport facilities was associated with 2.35 times higher odds to decreased overall physical activity compared to non-movers (30).

Better public transit availability assessed according to the number and distance to transit stops was associated with increased transportation-related walking in three studies, odds ratios ranging from 1.44 to 2.33 compared to participants with poorer access (25,31,32).

Park and playground improvements

Seven natural experiments assessed park and playground upgrades which included signage, promotional incentives, outreach and support for group activities, recreational areas, walking paths, play equipment, seating, safety surfacing and waste facilities. Park and playground improvements were associated with higher physical activity in five studies and the average quality of these studies was moderate (0.74, range: 0.65–0.81).

A new recreational park was associated with a three-fold increase in energy expended within the park boundaries and an increase in the total number of people observed using it (33). An increase of 7 to 12% in park use and an increase in energy expenditure of 610 MET-hours were found in another study after providing incentives and consultancy for marketing and outreach, and modifications or upgrades in facilities (34). New equipment, landscaping and ground surfaces were also associated with increases in park use ($\beta = 233.1$) and in MET-hours expended ($\beta = 254.8$) (35).

Significant renovations in park playfields in the US were associated with a five-fold increase in sedentary visitors, a three-fold increase in moderately active visitors and a two-fold increase in vigorously active visitors (36). After manipulating seating in a park playground, greater MET intensities were found when seating was not accessible (37). Following the intervention the odds for adults standing and being engaged in moderate to vigorous physical activity were 9.4 and 4.1, respectively when compared to sitting.

Street network characteristics

Improved street connectivity was associated with increased physical activity in five studies and decreased physical activity in two studies. On average, the quality of these studies was high (0.87, range: 0.68–0.95).

A recent study from the US revealed positive association between change in the network ratio of street connectivity and an increase in transportation walking by 1.81 min/week (21) whereas, in another study, the association was dependent on the urbanicity level categorized in tertiles based on Census tract-level population density (low, middle and high) (38). In low urbanicity areas, intersection density was positively associated with walking, bicycling and jogging (β = 1 – 1.3) while, in high density areas, both local road density and proportion of local roads had an inverse association with walking, biking and jogging frequencies in women (β = -1.3 – -1.4).

Moving to an area with fewer cul-de-sacs was associated with 757 more daily steps in American women (26). Increased exposure to pedestrian network intersections was associated with increased walking distance (β = 0.895) and walking ratio (β = 0.408) among Chinese university students (29). Two Australian studies revealed that relocation to a new, livable housing development with higher street connectivity was associated with 1.13 time higher odds for increased transportation-related walking and 1.2 times higher odds for taking up recreational cycling (25,39). Among Danish males, increased intersection density had a negative association with overall physical activity (β = -35.47) (22).

Density

Overall, four studies showed that higher population density was associated with more physical activity. The average quality of the studies was moderate (0.79, range: 0.68–0.86).

Higher housing density was associated with 2.72 times higher odds for increased utilitarian and 1.28 times higher odds for increased exercise walking compared to the least-dense areas among women (31). Moreover, women who moved to less-dense neighborhoods were 36% more likely to report decreased levels of utilitarian walking. An increase in population density was also associated with 3.8% increase in walking trips (32) and 1.54 higher odds to uptake transportation-related cycling (39). Higher population density was also related to increases in walking distance ($\beta = 0.187$) and walking altitude range ($\beta = 0.996$) (29).

Aggregate walkability measures

Higher walkability was associated with increased physical activity in three high quality studies (average quality score = 0.91, range: 0.86–0.95).

Two studies from North America assessed walkability with Walk Score which measures distances to different amenities. In a US study, moving to a location with ten-unit higher Walk Score was associated with an increase in transportation walking by 16.04 min/week (40). Among Canadian adults, moving from low to highly walkable neighborhoods (i.e. neighborhoods with two or three Walk Score quartile difference) increased the odds of utilitarian walking by 59% compared to moving to a neighborhood with the same walkability level (41). In young Danish women, an increase in the movability index was associated with an increase in overall physical activity ($\beta = 10.15$) (22). The movability index combined residential density, recreational facility area, density of daily destinations, and street connectivity.

Perceived built environment measures

An overview of the findings related to the perceived built environment measures and their association with the different domains of physical activity is presented in Figure 3.

Perceived BE measures	PA domain (number of studies)	*Number of associations obtained from different studies* 1	2	3	4	5	6	7	8
Accessibility (number of destinations, public transit availability)	Overall PA (n=1)	S, 0,77[42] N=1409							
	Transport PA (n=1)	S, 0,91[25] N=565	S, 0,91[25] N=565	S, 0,91[25] N=565	S, 0,86[39] N=1427	S, 0,86[39] N=1427	S, 0,86[39] N=1427	S, 0,86[39] N=1427	S, 0,86[39] N=1427
	Leisure time PA (n=3)	S, 0,91[43] N=9993	S, 0,86[39] N=1427	S, 0,86[39] N=1427	S, 0,86[39] N=1427	S, 0,73[45] N=1158			
Aesthetics (pleasantness and positive neighborhood features)	Overall PA (n=1)	S, 0,77[42] N=800							
	Transport PA (n=2)	S, 0,82[44] N=1142	S, 0,82[24] N=1420	S, 0,86[39] N=1427					
	Leisure time PA (n=2)	S, 0,82[24] N=1420	S, 0,73[45] N=1158	S, 0,86[39] N=1427					
Safety/unsafety (neighborhood safety, traffic and danger of walking and cycling, fear of crime)	Overall PA (n=3)	S, 0,86[11] N=1510	S, 0,82[47] N=485	S, 0,77[42] N=800					
	Transport PA (n=2)	S, 0,86[39] N=1427	S, 0,82[44] N=1142	S, 0,82[44] N=1142	S, 0,82[47] N=485				
	Leisure time PA (n=3)	S, 0,82[46] N=18900	S, 0,86[39] N=1427	S, 0,73[45] N=1158	S, 0,82[47] N=485				
Convenience (use of public transport, walking and cycling routes)	Overall PA (n=1)	S, 0,77[42] N=800							
	Transport PA (n=1)	S, 0,82[44] N=1142	S, 0,82[44] N=1142	S, 0,82[44] N=1142					
	Leisure time PA								
Barriers (barriers to walking and cycling, hilly streets)	Overall PA (n=1)	S, 0,86[57] N=750							
	Transport PA (n=1)	S, 0,86[39] N=1427							
	Leisure time PA (n=2)	S, 0,86[57] N=750	S, 0,86[39] N=1427	S, 0,86[39] N=1427					
Street network characteristics (street connectivity, pedestrian crossings)	Overall PA								
	Transport PA (n=1)	S, 0,91[25] N=565	S, 0,86[39] N=1427						
	Leisure time PA (n=1)	S, 0,86[39] N=1427							
Other (active school yards and playgrounds, residential density, visibility, change in infrastructure)	Overall PA (n=2)	O, 0,82[48] N=736	S, 0,86[11] N=1510	S, 0,86[11] N=1510	S, 0,82[48] N=736	O, 0,82[48] N=736			
	Transport PA (n=1)	S, 0,91[25] N=565							
	Leisure time PA (n=1)	S, 0,82[48] N=736							

Statistically significant positive association

Null association

Statistically significant negative association

Figure 3. Number of associations between perceived built environment (BE) measures and physical activity (PA). Characters in the cells: O = objectively measured physical activity, S = self-reported physical activity, Quality score^{reference}, N = Sample size.

Accessibility

Better perceived access to destinations was associated with increased physical activity in two high quality studies (average quality score = 0.89, range: 0.86–0.91).

Increased perceived access to parks (OR = 2.60) and recreation destinations (OR = 1.57) were associated with an increase in transportation-related cycling after relocation to a new livable housing development among Australian adults (39). Also, among the same study population, the odds for transportation related walking were 3.11 times higher for participants who perceived higher number of destinations, 1.27 times higher for those living in environments with better land use mix and 1.80 times higher for those with access to a railway station in their neighborhood (25).

An increase in perceived number of neighborhood sport facilities was associated with increased weekly frequency of leisure time moderate to vigorous physical activity (β = 1.07) among adolescent students who engaged in leisure-time physical activity more than three times a week at baseline (43).

Aesthetics

A higher sense of aesthetics was associated with improved physical activity in all of the four studies that assessed the pleasantness and positive features of neighborhoods. The average quality score for these studies was moderate (0.79, range: 0.73–0.82).

Men who increased their perception of aesthetics of the neighborhood were 2.25 times more likely to increase in overall walking compared to those who did not change their perception (42). Another study revealed that each additional neighborhood feature perceived to have changed favorably was associated with increased walking for transportation by 3.0 min/week and increased recreational walking by 2.2 min/week (24). According to a UK study, perceiving one's commuting route as less pleasant to walk was associated with less time spent walking while commuting (β = -11.94) (44). Austrian women who reported poor health and found their neighborhoods unattractive had 2.7 times greater likelihood to regress from regular running than women who perceived their neighborhoods as attractive (45).

Safety

Perceived neighborhood safety was associated with increased physical activity in one study, and traffic and crime related unsafety with decreased physical activity in three studies. The average quality of these studies was moderate (0.80, range: 0.77–0.86).

Changes in parents' perceptions of neighborhood safety from "very safe" to "somewhat or not at all safe" was associated with 0.13 fewer weekly days of vigorous physical activity among American children (46). If traffic was not perceived as a problem, men appeared to walk less (OR = 0.40) but women more (OR = 1.76) (42). In another study, each one level increase in fear of crime on a five point Likert-scale was associated with reduced total walking by 22 mean minutes/week and reduced recreational walking by 13 mean minutes/week within the neighborhood (47). In addition, the use of new routes for walking and cycling predicted 1.31 higher odds for improved perceptions of safety in the UK (11).

Convenience

An Australian study with a moderate quality score (0.77) found that if participants perceived greater convenience of walking opportunities in their neighborhood they were twice as likely to increase walking (42).

Other effects of changes in the built environment

Town level initiatives to enhance cycling were associated with 0.32 percentage point increase in the use of public transportation and three percentage point decrease in the prevalence of driving to work (12). New rail stops were associated with decreased car rides (β = 6.44) among new users of public transportation (16) and new railway corridors with reduced driving among households who valued transit-oriented development features (18).

New busways with parallel paths for walking and cycling were associated with over 30% decrease in trips made by car (15). A US study showed that increased neighborhood accessibility was associated with reduced vehicle (β = -5.76) and person miles travelled (β = -6.79) and number of trips per tour (β = -0.19) but increased number of tours (β = 0.26) (49). In the same study, increased regional and workplace accessibility was related to reduced driving (49).

A study from the UK revealed multiple associations related to perceived changes in commuting route and travel mode (44). More convenient public transportation was associated with using other methods of commuting than private cars (OR = 3.31). If the route was perceived to become less pleasant to walk or more dangerous when cycling or crossing roads, driving increased (β = 5.22 – 7.57). If the route was perceived as less dangerous to cycle, cars were used less for commuting (OR = 3.70). In another study, a new dedicated bike lane was associated with a 57% increase in the number of cyclists (50). A new bike lane was also associated with an increase in the average number of cyclists from 79.2 to 257.1 on an intervention street whereas on the adjacent control streets the number of cyclists decreased from 54.4 to 36.3 (51).

Discussion

Summary of evidence

This extensive systematic review aimed to identify the determinants of the built environment associated with physical activity and to evaluate how changes in the built environment are associated with changes in physical activity. This is the first review with focus on studies using longitudinal design i.e. prospective longitudinal cohort studies and natural experiments, which implies the highest level of evidence to date about this topic. Moreover, the analysis was stratified based on different domains of physical activity, which should strengthen the evidence base. The high-quality evidence showed that changes in the built environment were associated with increased transportation-related and overall physical activity.

A considerable number of studies indicated that creating new infrastructure for walking, cycling and public transportation were related to increased physical activity. The findings were most consistent for transportation-related and overall physical activity, which were especially associated with the creation of new trails for walking and cycling. In addition to increased physical activity, new infrastructure for walking, cycling and public transportation was associated with decreased use of private cars in four studies (12,15,16,18).

The findings from the natural experiments are promising in terms of increasing physical activity and reducing the use of private motor vehicles by making the built environment more supportive for walking, cycling and public transportation. This would imply that behavior is responsive to changes in the built environment and demand for active transportation can be induced, which would have direct implications for greater investments into high quality infrastructure for these active modes of transportation in order to make the modal shift from private motor vehicles possible. However, many of the natural experiments suffered from methodological weaknesses, so the results must be interpreted with caution.

A higher objectively measured accessibility was associated with increased transportation-related and overall physical activity in high quality studies. In terms of transportation-related physical activity, the results originated from four study populations, and all showed positive association (21,24,25,31,32). The strongest evidence was found for the number of destinations with four positive associations indicating an increase from 3.3 to 17.6 min/week or showing 1.4 times higher odds for increased physical activity. A higher land use mix also increased walking in two studies. In addition, availability of public transportation was associated with increased transportation walking in three studies. Regarding overall physical activity, majority of the studies showed positive association (22,26,29,30). The findings provide implications for zoning policy and support the creation of compact and diverse residential areas where housing is mixed with commercial, public and recreational destinations and the circumstances for daily living are located within walking and cycling distance.

For objectively measured street network connectivity and population density, the evidence was more mixed and was limited to the few studies assessing these features. Higher street connectivity was associated with increased overall physical activity in three studies (26,29,38) and transportation-related physical activity in two studies (21,25), but there were also two negative and several null associations. Increased population density was positively associated with increased transportation-related physical activity in three out of four studies (31,32,39).

Also, few longitudinal studies have evaluated aggregated walkability measures and their association to physical activity. Three high quality studies indicated that improved walkability is related to higher physical activity (22,40,41). Based on the studies included in the present review, park and playground improvements seem to be a feasible strategy to enhance overall physical activity. However, these studies suffered from methodological weaknesses which render it difficult to evaluate the true impact on physical activity.

In terms of the perceived built environment measures, four studies showed positive associations between pleasantness and positive neighborhood features and physical activity (24,42,44,45). Also, environments considered safe were associated with more overall physical activity and leisure time physical activity in four studies (11,42,46,47). The perceived number of destinations and public transit availability were associated with transportation-related physical activity in the RESIDential Environment Study (RESIDE) in Australia. Because the five positive associations were observed only in two studies (25,39) within the same study population, general conclusions cannot be drawn about perceived accessibility. Overall, ten studies did not find significant associations between changes in the built environment and changes in physical activity (56-65).

Physical activity occurs in multiple domains and ecological models emphasize domain-specific and context specific environmental influences which should be conceptually matched (7). This review showed that increase in overall physical activity was mostly associated with creation of new infrastructure for walking, cycling and public transportation; park and playground improvements; and objectively measured accessibility. Only few studies assessed changes in perceived built environment measures and their association with changes in overall physical activity. Two out of three studies indicated that environments considered more unsafe were associated with declined overall physical activity. In terms of transportation related physical activity, the review showed that improved objectively measured accessibility and new infrastructure for walking, cycling and public transportation were associated with increased physical activity. Moreover, improved perception of aesthetics was associated with transportation related physical activity in two out of three studies. In terms of leisure-time physical activity, no uniform associations were found.

Thus far, the studies concerning longitudinal association between the built environment and physical activity have suggested that street and pedestrian connectivity, land use and destination mix, and overall neighborhood design are important factors for supporting physical activity among adults (6). However, the majority of this evidence originated from cross-sectional studies that adjusted for neighborhood self-selection. Previous evidence from cross-sectional studies also indicate that high population density is correlated with increased physical activity (6,54). This is also considered a prerequisite for creating neighborhoods where housing is mixed with commercial and recreational destinations and where public transit is easily accessible (3). Moreover, a study that compared 11 countries revealed a correlation between aesthetics and safety with moderate to vigorous physical activity (55).

The findings related to objectively measured accessibility are in line with previous cross-sectional evidence suggesting that mixed land use and accessibility of different types of destinations and public transit contribute to population-level transportation-related physical activity in urban settings among adults (52,53). The results of the present review show that land use and destination mix can result in increased transportation-related and overall physical activity. Moreover, we found some evidence that perceived aesthetics and safety can affect physical activity. In terms of objectively measured street connectivity, population density and other perceived built environment measures, no valid conclusions could be drawn due to the limited number of studies.

Regarding the quality of the examined research, the risk of bias was lower in prospective longitudinal cohort studies compared to natural experiments. Also, a recent review concerning the risk of bias in natural experiments concluded that they suffer from methodological limitations in a number of key bias domains (70). In terms of natural experiments, the use of control groups, longer follow-up and exposure times as well as more advanced methods for assessing the exposure to the experiment are needed to detect the true effects on behavior. Moreover, only five studies used objectively measured physical activity as the main outcome and the recall bias is a common problem with self-reported physical activity measures. There were 22 studies with a quality score of 0.85 or above. Also, within these high-quality studies, the results reflect that new infrastructure for walking, cycling and public transportation is associated with increased overall physical activity and transportation-related physical activity and that accessibility is associated with transportation-related physical activity.

The research field is evolving rapidly, particularly in terms of more advanced study designs. However, longitudinal studies and natural experiments are not free from confounding. True experimental studies assessing changes in the built environment and their effect on physical activity will most likely never be feasible, so the methodology of observational studies and natural experiments needs to be enhanced.

It is essential to adjust for people’s reasons for selecting a specific place to live and their general attitudes towards active transportation, a topic that has been broadly discussed elsewhere (66-68). Residential mobility and motivations for changing residences have been shown to involve a complex interplay between age, family status and timing of life events (69). They primarily emanate from factors related to quality of life, such as improved housing, neighborhoods, commuting and health benefits, and in addition, family reasons are important for choosing a specific place to live (69).

An individual might, for example, choose a place of residence in a car-dominant neighborhood based on the area's affordable housing. Even in this case, physical activity might actually increase due to longer distances to amenities if attitudes towards active transportation are positive. In the present review, the majority (80%) of the studies did not adjust for residential self-selection. Some used fixed effects models to adjust for unmeasured within-person confounders that are stable over time. Still, the possibility remains that, for example, people's attitudes might change during the follow-up.

Recently, an international comparative study revealed that, among adults, living in an activity-friendly neighborhood was associated with 68 to 89 min more physical activity than living in a non-activity-friendly neighborhood (54). The findings were generally similar across diverse cities in different countries, which would imply that physical activity can be increased in different settings with similar built environment characteristics. Only a few longitudinal studies focused on different settings (such as rural and sparsely populated areas) or on low-income countries, which are recommended areas of research for future longitudinal studies. More research on different age groups is required to make stratification possible. Thus far, mostly adults have been studied. Further studies on perceived measures of the built environment as determinants of physical activity are also needed.

Strengths and limitations of the review

The present review has multiple strengths. We conducted an extensive search of publications from six databases and evaluated the quality of the evidence. We assessed the primary measure of effects according to changes in the built environment and their association with changes in physical activity. Moreover, we were able to stratify the analysis according to the domain of physical activity and the built environment measurement type.

The review also has limitations. We focused solely on peer-reviewed publications and did not conduct a search for grey literature, which might introduce publication bias. Age stratification was not feasible because the population of most of the studies consisted of adults. Most studies were also conducted in urban settings and in high-income countries. Hence, the applicability of the results to different populations or settings is somewhat limited. Furthermore, the heterogeneity of the studies and the diversity of outcome and exposure measures prevented us from conducting a meta-analysis. We extracted the statistically significant associations from original studies using the most adjusted model. An alternative would have been to use the results with minimum adjustments to make the effect sizes of different studies more comparable. Since we were not able to conduct a quantitative meta-analysis, we expect that the use of the most adjusted models will not bias our results. In addition, the built environment categories used to derive the results are potentially heterogeneous, and the different exposure measures included in those might be defined conceptually and computationally in different ways.

Conclusions

The findings from this review support the hypothesis that urban and transport planning have an effect on physical activity of the citizens. The review showed that improved objectively measured accessibility assessed with the number of different type of destinations, access to public transportation, and land use mix was associated with increased transportation related physical activity. The evidence also suggests that transportation-related and overall physical activity could be increased and the use of private motor vehicles reduced by creating new infrastructure for walking, cycling and public transportation.

The results provided support for the benefits of designing activity-friendly and health-enhancing cities and living environments. The findings have implications for zoning policy and support the creation of compact and diverse residential areas where housing is mixed with commercial, public and recreational destinations in order to enhance everyday physical activity. Moreover, investments into infrastructure for active modes of transportation could reinforce the modal shift from private motor vehicles into walking, cycling and public transportation. Further studies with more rigorous study designs assessing changes in the built environment and their effects on physical activity are warranted to ascertain causalities and to assess the effects of other factors of the built environment.

References

1. Ding D, Lawson KD, Kolbe-Alexander TL, et al. The economic burden of physical inactivity: A global analysis of major non-communicable diseases. *Lancet*. 2016, 388:1311-1324.

2. Sallis JF, Bull F, Burdett R, et al. Use of science to guide city planning policy and practice: How to achieve healthy and sustainable future cities. *Lancet*. 2016, 388:2936-2947.

3. Giles-Corti B, Vernez-Moudon A, Reis R, et al. City planning and population health: A global challenge. *Lancet*. 2016, 388:2912-2924.

4. Stevenson M, Thompson J, de Sa TH, et al. Land use, transport, and population health: Estimating the health benefits of compact cities. *Lancet*. 2016, 388:2925-2935.

5. Ding D, Gebel K. Built environment, physical activity, and obesity: What have we learned from reviewing the literature? *Health Place*. 2012, 18:100-105.

6. McCormack GR, Shiell A. In search of causality: A systematic review of the relationship between the built environment and physical activity among adults. *Int J Behav Nutr Phys Act*. 2011, 8:125.

7. Gebel K, Ding D, Foster C, Bauman AE, Sallis JF. Improving current practice in reviews of the built environment and physical activity. *Sports Med*. 2015, 45:297-302.

8. Moher D, Liberati A, Tetzlaff J, Altman DG, PRISMA Grp. Preferred reporting items for systematic reviews and meta-Analyses: The PRISMA statement. *Ann Intern Med*. 2009, 151:264-W64.

9. Kmet LM, Lee RC, Cook LS. Standard quality assessment criteria for evaluating primary research papers from a variety of fields. Edmonton: Alberta Heritage Foundation for Medical Research (AHFMR). HTA Initiative #13. 2004.

10. Goodman A, Sahlqvist S, Ogilvie D, Connect Consortium. New walking and cycling routes and increased physical activity: One- and 2-year findings from the UK iConnect study. *Am J Public Health*. 2014, 104:E38-E46.

11. Panter J, Ogilvie D, iConnect Consortium. Theorising and testing environmental pathways to behaviour change: Natural experimental study of the perception and use of new infrastructure to promote walking and cycling in local communities. *Bmj Open*. 2015, 5:e007593.

12. Goodman A, Panter J, Sharp SJ, Ogilvie D. Effectiveness and equity impacts of town-wide cycling initiatives in England: A longitudinal, controlled natural experimental study. *Soc Sci Med*. 2013, 97:228-237.

13. Fitzhugh EC, Bassett DR, Jr., Evans MF. Urban trails and physical activity: A natural experiment. *Am J Prev Med*. 2010, 39:259-262.

14. Rissel C, Greaves S, Wen LM, Crane M, Standen C. Use of and short-term impacts of new cycling infrastructure in inner-Sydney, Australia: A quasi-experimental design. *Int J Behav Nutr Phys Act*. 2015, 12:1.

15. Heinen E, Panter J, Mackett R, Ogilvie D. Changes in mode of travel to work: A natural experimental study of new transport infrastructure. *International Journal of Behavioral Nutrition and Physical Activity*. 2015, 12:81.

16. Brown BB, Werner CM. Before and after a new light rail stop: Resident attitudes, travel behavior, and obesity. *Journal of the American Planning Association*. 2009, 75:5-12.

17. Brown BB, Werner CM. A new rail stop - Tracking moderate physical activity bouts and ridership. *Am J Prev Med*. 2007, 33:306-309.

18. Curtis C, Olaru D. The impacts of a new railway: travel behaviour of residents in new station precincts. In: Viegas JM and Macario R, eds. 12th World Transport Research Conference. Lisbon, Portugal: World Transport Research Conference; 2010, 25.

19. McDonald NC, Yang Y, Abbott SM, Bullock AN. Impact of the Safe Routes to School program on walking and biking: Eugene, Oregon study. *Transp Policy*. 2013, 29:243-248.

20. Burbidge S, Goulias K. Evaluating the impact of neighborhood trail development on active travel behavior and overall physical activity of suburban residents. *Transportation Research Record: Journal of the Transportation Research Board*. 2009, 2135:78-86.

21. Hirsch JA, Moore KA, Clarke PJ, et al. Changes in the built environment and changes in the amount of walking over time: Longitudinal results from the Multi-Ethnic study of Atherosclerosis. *Am J Epidemiol*. 2014, 180:799-809.

22. Schipperijn J, Ried-Larsen M, Nielsen MS, et al. A longitudinal study of objectively measured built environment as determinant of physical activity in young adults: The European Youth Heart Study. *J Phys Act Health*. 2015, 12:909-914.

23. Western Australian Planning Commission. *Liveable neighbourhoods: A Western Australian government sustainable cities initiative.* Perth: Western Australian Planning Commission. 2004.

24. Giles-Corti B, Bull F, Knuiman M, et al. The influence of urban design on neighbourhood walking following residential relocation: longitudinal results from the RESIDE study. *Soc Sci Med*. 2013, 77:20-30.

25. Knuiman MW, Christian HE, Divitini ML, et al. A longitudinal analysis of the influence of the neighborhood built environment on walking for transportation: the RESIDE study. *Am J Epidemiol*. 2014, 180:453-461.

26. Wells NM, Yang Y. Neighborhood design and walking. A quasi-experimental longitudinal study. *Am J Prev Med*. 2008, 34:313-319.

27. Ranchod YK, Diez Roux AV, Evenson KR, Sanchez BN, Moore K. Longitudinal associations between neighborhood recreational facilities and change in recreational physical activity in the multi-ethnic study of atherosclerosis, 2000-2007. *Am J Epidemiol*. 2014, 179:335-343.

28. Boone-Heinonen J, Guilkey DK, Evenson KR, Gordon-Larsen P. Residential self-selection bias in the estimation of built environment effects on physical activity between adolescence and young adulthood. *Int J Behav Nutr Phys Act*. 2010, 7:70.

29. Sun G, Oreskovic NM, Lin H. How do changes to the built environment influence walking behaviors? A longitudinal study within a university campus in Hong Kong. *Int J Health Geogr*. 2014, 13:28.

30. Halonen JI, Stenholm S, Kivimaki M, et al. Is change in availability of sports facilities associated with change in physical activity? A prospective cohort study. *Prev Med*. 2015, 73:10-14.

31. Coogan PF, White LF, Adler TJ, Hathaway KM, Palmer JR, Rosenberg L. Prospective study of urban form and physical activity in the Black Women's Health Study. *Am J Epidemiol*. 2009, 170:1105-1117.

32. Joh K, Chakrabarti S, Boarnet MG, Woo A. The walking renaissance: A longitudinal analysis of walking travel in the Greater Los Angeles Area, USA. *Sustainability*. 2015, 7:8985-9011.

33. King DK, Litt J, Hale J, Burniece KM, Ross C. 'The park a tree built': Evaluating how a park development project impacted where people play. *Urban Forestry & Urban Greening*. 2015, 14:293-299.

34. Cohen DA, Han B, Derose KP, Williamson S, Marsh T, McKenzie TL. Physical activity in parks: A randomized controlled trial using community engagement. *Am J Prev Med*. 2013, 45:590-597.

35. Cohen DA, Han B, Isacoff J, et al. Impact of Park Renovations on Park Use and Park-Based Physical Activity. *Journal of Physical Activity & Health*. 2015, 12:289-295.

36. Tester J, Baker R. Making the playfields even: evaluating the impact of an environmental intervention on park use and physical activity. *Prev Med*. 2009, 48:316-320.

37. Roemmich JN, Beeler JE, Johnson L. A microenvironment approach to reducing sedentary time and increasing physical activity of children and adults at a playground. *Prev Med*. 2014, 62:108-112.

38. Hou N, Popkin BM, Jacobs DRJ, et al. Longitudinal associations between neighborhood-level street network with walking, bicycling, and jogging: the CARDIA study. *Health Place*. 2010, 16:1206-1215.

39. Beenackers MA, Foster S, Kamphuis CB, et al. Taking up cycling after residential relocation: Built environment factors. *Am J Prev Med*. 2012, 42:610-615.

40. Hirsch JA, Diez Roux AV, Moore KA, Evenson KR, Rodriguez DA. Change in walking and body mass index following residential relocation: The multi-ethnic study of atherosclerosis. *Am J Public Health*. 2014, 104:e49-56.

41. Wasfi RA, Dasgupta K, Eluru N, Ross NA. Exposure to walkable neighbourhoods in urban areas increases utilitarian walking: Longitudinal study of Canadians. *J Transp Health*. 2015, 3:440-447.

42. Humpel N, Marshall AL, Leslie E, Bauman A, Owen N. Changes in neighborhood walking are related to changes in perceptions of environmental attributes. *Annals of Behavioral Medicine*. 2004, 27:60-67.

43. Wong BY, Ho SY, Lo WS, Cerin E, Mak KK, Lam TH. Longitudinal relations of perceived availability of neighborhood sport facilities with physical activity in adolescents: An analysis of potential moderators. *J Phys Act Health*. 2014, 11:581-587.

44. Panter J, Griffin S, Ogilvie D. Active commuting and perceptions of the route environment: A longitudinal analysis. *Prev Med*. 2014, 67:134-140.

45. Titze S, Stronegger W, Owen N. Prospective study of individual, social, and environmental predictors of physical activity: Women's leisure running. *Psychol Sport Exerc*. 2005, 6:363-376.

46. Datar A, Nicosia N, Shier V. Parent perceptions of neighborhood safety and children's physical activity, sedentary behavior, and obesity: evidence from a national longitudinal study. *Am J Epidemiol*. 2013, 177:1065-1073.

47. Foster S, Knuiman M, Hooper P, Christian H, Giles-Corti B. Do changes in residents' fear of crime impact their walking? Longitudinal results from RESIDE. *Prev Med*. 2014, 62:161-166.

48. De Meester F, Van Dyck D, De Bourdeaudhuij I, Deforche B, Cardon G. Changes in physical activity during the transition from primary to secondary school in Belgian children: What is the role of the school environment? *BMC Public Health*. 2014, 14:261.

49. Krizek KJ. Residential relocation and changes in urban travel - Does neighborhood-scale urban form matter? *Journal of the American Planning Association*. 2003, 69:265-281.

50. Parker KM, Gustat J, Rice JC. Installation of bicycle lanes and increased ridership in an urban, mixed-income setting in New Orleans, Louisiana. *Journal of Physical Activity & Health*. 2011, 8:98-102.

51. Parker KM, Rice J, Gustat J, Ruley J, Spriggs A, Johnson C. Effect of bike lane infrastructure improvements on ridership in one New Orleans Neighborhood. *Annals of Behavioral Medicine*. 2013, 45:101-107.

52. Cerin E, Leslie E, du Toit L, Owen N, Frank LD. Destinations that matter: Associations with walking for transport. *Health Place*. 2007, 13:713-724.

53. Saelens BE, Handy SL. Built environment correlates of walking: A review. *Med Sci Sports Exerc*. 2008, 40:550-566.

54. Sallis JF, Cerin E, Conway TL, et al. Physical activity in relation to urban environments in 14 cities worldwide: A cross-sectional study. *Lancet*. 2016, 387:2207-2217.

55. Cerin E, Cain KL, Conway TL, et al. Neighborhood environments and objectively measured physical activity in 11 countries. *Med Sci Sports Exerc*. 2014, 46:2253-2264.

56. Coombes E, Jones A, Page A, Cooper AR. Is change in environmental supportiveness between primary and secondary school associated with a decline in children's physical activity levels? *Health Place*. 2014, 29:171-178.

57. Dawson J, Hillsdon M, Boller I, Foster C. Perceived barriers to walking in the neighbourhood environment and change in physical activity levels over 12 months. *BJSM online*. 2007, 41:562-568.

58. Lee IM, Ewing R, Sesso HD. The built environment and physical activity levels: the Harvard Alumni Health Study. *Am J Prev Med*. 2009, 37:293-298.

59. Dill J, McNeil N, Broach J, Ma L. Bicycle boulevards and changes in physical activity and active transportation: Findings from a natural experiment. *Prev Med*. 2014, 69:74-8.

60. Ward Thompson C, Curl A, Aspinall P, Alves S, Zuin A. Do changes to the local street environment alter behaviour and quality of life of older adults? The 'DIY Streets' intervention. *BJSM online*. 2014, 48:1059-1065.

61. Cohen DA, Golinelli D, Williamson S, Sehgal A, Marsh T, McKenzie TL. Effects of park improvements on park use and physical activity policy and programming implications. *Am J Prev Med*. 2009, 37:475-480.

62. Quigg R, Reeder AI, Gray A, Holt A, Waters D. The effectiveness of a community playground intervention. *J Urban Health*. 2012, 89:171-184.

63. Evenson KR, Herring AH, Huston SL. Evaluating change in physical activity with the building of a multi-use trail. *Am J Prev Med*. 2005, 28:177-185.

64. MacDonald JM, Stokes RJ, Cohen DA, Kofner A, Ridgeway GK. The effect of light rail transit on body mass index and physical activity. *Am J Prev Med*. 2010, 39:105-112.

65. Christian H, Knuiman M, Bull F, et al. A new urban planning code's impact on walking: The residential environments project. *Am J Public Health*. 2013, 103:1219-1228.

66. Mokhtarian PL, Cao X. Examining the impacts of residential self-selection on travel behavior: A focus on methodologies. *Transp Res Pt B-Methodol*. 2008, 42:204-228.

67. van de Coevering P, Maat K, van Wee B. Multi-period research designs for identifying causal effects of built environment characteristics on travel behaviour. *Transp Rev*. 2015, 35:512-532.

68. Boone-Heinonen J, Gordon-Larsen P, Guilkey DK, Jacobs DR, Popkin BM. Environment and physical activity dynamics: The role of residential self-selection. *Psychol Sport Exerc*. 2011, 12:54-60.

69. Geist C, McManus PA. Geographical mobility over the life course: Motivations and implications. *Popul Space Place*. 2008, 14:283-303.

70. Benton JS, Anderson J, Hunter RF, French DP. The effect of changing the built environment on physical activity: A quantitative review of the risk of bias in natural experiments. *Int J Behav Nutr Phys Act*. 2016, 13:107.

Figure captions

Figure 1. PRISMA flow diagram of the study selection process

Figure 2. Figure 2. Number of associations between objective built environment (BE) measures and physical activity (PA). Characters in the cells: O = objectively measured physical activity, S = self-reported physical activity, Quality score[reference], N = Sample size.

Figure 3. Number of associations between perceived built environment (BE) measures and physical activity (PA). Characters in the cells: O = objectively measured physical activity, S = self-reported physical activity, Quality score[reference], N = Sample size.