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Title

Built environment and cardio-metabolic health: systematic review and meta-analysis of longitudinal studies

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Conflicts of interest

The authors report no conflicts of interest.

Author contributions

MC and TS conceived the study. All authors contributed to the initial planning of the review. MC, JR, LG, and TS developed the search strategy. MC performed database searches. MC, JR, and LG independently screened titles and abstracts, read full articles, and extracted data. TS mediated the discrepancies in article screening. MC and TS developed the quality assessment tool with inputs from all authors. MC assessed study quality, and performed meta-analysis. MC and TS drafted the manuscript. All authors contributed to reviewing and revising the manuscript, read and approved the final manuscript

ABSTRACT

Built environment attributes may be related to cardio-metabolic diseases (e.g., type 2 diabetes, heart disease, and stroke) and their risk factors, potentially by influencing residents' physical activity. However, existing literature reviews on the built environment and health for the most part focus on obesity as the outcome, and rely on cross-sectional studies. This systematic review synthesized current evidence on longitudinal relationships between built environment attributes and cardio-metabolic health outcomes among adults, and on the potential mediating role of physical inactivity. By searching eight databases for peer-reviewed journal articles published in the English language between January 2000 and July 2016, the review identified 36 articles. A meta-analysis method, *weighted Z-test*, was used to quantify the strength of evidence by incorporating the methodological quality of the studies. We found strong evidence for longitudinal relationships of walkability with obesity, type 2 diabetes, and hypertension outcomes in the expected direction. There was strong evidence for the impact of urban sprawl on obesity outcomes. The evidence on potential mediation by physical activity was inconclusive. Further longitudinal studies are warranted to examine which specific built environment attributes influence residents' cardio-metabolic health outcomes and how physical inactivity may be involved in

these relationships.

Key words: Urban design, Walkability, Obesity, Type 2 diabetes, Hypertension

INTRODUCTION

Type 2 diabetes (T2D) and cardiovascular disease (CVD) are leading causes of poor health, disability, and death, and their burden is rising globally (1, 2). There are established markers of cardio-metabolic risk, including abdominal adiposity, glucose intolerance, hypertension, and dyslipidemia, which can predispose individuals to developing T2D and CVD (3). Given that T2D and CVD are regarded as having significant preventable components (4, 5), there have been calls for population-wide public health initiatives to address their major behavioral risk factors, which include physical inactivity, unhealthy diet, and cigarette smoking (6). Considering that physical inactivity is highly prevalent worldwide (7), there is growing interest in the role of neighborhood built environments, which potentially support residents' active lifestyles, in preventing cardio-metabolic diseases (8, 9).

A number of systematic reviews of studies on relationships between built environment attributes and adults' cardio-metabolic health outcomes have been published (10-17). However, these reviews summarized evidence based mostly on cross-sectional studies; hence, they do not support causal inferences. In addition, these systematic reviews focused primarily on obesity-related outcomes, with only a few considering a range of cardio-metabolic health outcomes (14, 16). Evidence from longitudinal studies needs to be synthesized to identify attributes of built environments that may be protective against the development of T2D and CVD (9).

Built environment attributes may influence residents' health, partly through physical activity and sedentary behavior (18). The ecological model of health behavior postulates that multi-level factors (e.g., individual, social, environmental, and policy) can influence behaviors, emphasizing the role of "behavior settings"- those attributes of environmental contexts that can act to promote certain behaviors and discourage others (19). Identifying the built environment attributes that are supportive of habitually active lifestyles is a public health research priority. Environmentally-focused initiatives are argued to have the potential to be effective, even in the absence of a conscious intention, for example, to be physically active (20). Previous studies show that lack of physical activity and prolonged sedentary behavior can independently elevate the risk of developing T2D and CVD (21, 22). Literature reviews also identify consistent relationships between certain built environment attributes (e.g., residential density, street connectivity, availability of diverse destinations, public open space, and their composite measures such as walkability) and different types of physical activities (e.g., walking, leisure-time physical activity) and sedentary behaviors (e.g., car use, television watching) in adults (23-26). However, it is not clear to what extent these behaviors may mediate longitudinal relationships between built environments and cardio-metabolic health.

We systematically reviewed longitudinal studies on the relationships between built environment attributes and cardio-metabolic health outcomes in adults and quantified the strength of evidence using a meta-analytic approach that accounted for the methodological quality of the studies. We also synthesized any relevant evidence on how physical activity and sedentary behavior may mediate the longitudinal relationships.

METHODS

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (27) were followed in this review.

Search Strategy

A reproducible systematic search of peer-reviewed journal articles published in the English language between January 2000 and July 2016 was undertaken by the first author (MC) using eight electronic databases: Medline; Web of Science; Cochrane; Embase; PsycInfo; CINHAL; Scopus; and Transport Research International Documentation (TRID). Three sets of search terms on built environment, cardio-metabolic health, and longitudinal design were used. Search terms for each category were developed based on those used in other related reviews (14, 15, 26, 28). A full description of the search terms is provided in Supporting Information (Table S1).

Inclusion/Exclusion Criteria

Studies were included if they met the following four criteria:

1. *Exposures*: Objectively-measured (using geographic information systems) or perceived (using questionnaires) built environment attributes
2. *Outcomes*: Objectively-measured (by biomedical examination) or self-reported (using questionnaires) cardio-metabolic health outcomes; including incidence of diseases, and biomarkers.
3. *Study designs*: Longitudinal design quantitatively examining the relationships between exposures and outcomes
4. *Participants*: Adults, aged 18 years and older

One exclusion criterion was based on how studies postulated a link between the built environment and cardio-metabolic health. To sustain a manageable scope and coherence, we focused on studies that postulated physical activity or sedentary behavior as a pathway, and excluded studies postulating other mechanisms, such as food environment, air/noise pollution, access to healthcare, sanitation, and climate change. We also excluded studies focused specifically on clinically-defined sub-groups (e.g., those who were pregnant, with diabetes, had stroke), and those studies focusing on participants' workplace and its vicinity.

Screening Process

Articles were reviewed independently by three authors (MC, JR, and LG). At all stages of the review process (title and abstract screening, full article selection, data extraction), MC reviewed 100% of the articles, with JR and LG each reviewing 60% of the articles with an overlap of 20%. Discrepancies between the reviewers at each stage were mediated by TS.

Data Extraction

The following information was extracted from each article:

1. *Study*: author, year (published), project/cohort name
2. *Location*: country, multi-site or not
3. *Sample*: size, demographic information, recruitment strategy (particularly, if study areas were purposefully selected to have a diversity in environmental attributes or not)
4. *Design*: study design (observational, natural experimental), follow-up duration, number of waves, residential relocation
5. *Response rate*: at baseline, retention at follow-up(s)
6. *Measures*: outcomes (including methods), exposures (including methods, area unit, examined environmental changes or not), mediators, moderators, individual-level and area-level confounders
7. *Analyses*: statistical methods, accounting for area-level clustering or not, adjusting for residential self-selection or not, and drop-out analysis
8. *Results*: magnitude and direction of relationships, statistical significance, mediation (physical activity and/or sedentary behavior)

Coding and Counting of Findings

A statistically-significant relationship was coded as [E] if it was in the expected direction (i.e., built environment attributes supporting physical activity, such as high walkability, being associated with reduced cardio-metabolic risk) or [U] if it was in the unexpected direction. A statistically non-significant relationship was coded as null [N]. To avoid over-representation of findings from the same data set, reported relationships in the articles were counted using a method introduced in a previous review (23): if the relationship of a specific environmental exposure with a specific cardio-metabolic outcome (e.g., walkability and obesity) using the same data source was reported in more than one article, the finding from the article that scored a higher methodological quality score (detail explained below) was counted; if an article examined a specific exposure-outcome relationship within a study using the exposure calculated in different types of geographical units (e.g., administrative units and individual buffers) or at different scales (e.g., 400m and 1000m buffers), each finding was assigned an equal fractional weight in such a way that the sum of the weights equals to one; if a specific exposure-outcome relationship was examined separately for subgroups (e.g., men and women) within a study, the findings were considered as distinct only if they differed in direction or statistical significance. In such cases, each finding was assigned a fractional weight proportional to the sample size of the subgroup.

Methodological Quality Assessment

It is recommended that systematic reviews of built environment and health research should consider the methodological quality of the reviewed articles to synthesize and interpret the findings (29). Cerin et al. developed a quality assessment tool to assess the methodological quality of cross-sectional studies on built environment attributes and physical activity (23). Barnett et al. (30) extended this tool by adding an item to assess the study design. The assessment items in the original tool included: [1] sample representativeness; [2] study design; [3] exposure variability (study areas selected to maximize the variability in the exposure variables); [4] adjustment for individual socio-demographic covariates; [5]

adjustment for residential self-selection; [6] accounting for area-level clustering; and [7] appropriate presentation of analysis results. We adapted and further extended this tool by adding items relevant to longitudinal design, measurement of built environment attributes, and measurement of cardio-metabolic health outcomes. For aspects relevant to longitudinal design, we included the following items based on the quality assessment checklist developed by Tooth et al. (31): [8] follow-up duration; [9] number of data collection time points; [10] participant retention rate; and [11] appropriate longitudinal data analysis. We further included items specific to the measurement of exposures and outcomes, following Giles-Corti et al. (32). These included: [12] measurement of built environment attributes (appropriate geographical unit and size to capture participants' neighborhood for objective measures or use of validated survey instruments for perceived measures); [13] measurement of health outcome (objectively-measured vs self-reported); and [14] temporal match of exposure and outcome measures.

For each assessment item, a score of 0.0 (not meeting the quality criterion) or 1.0 (meeting the quality criterion) was assigned. An intermediate score of 0.5 was assigned for an acceptable level for relevant items. Items 6, 7, and 11 (used for assessing the quality of statistical analysis) were assigned a score of 0 or 1/3 to avoid over-scoring for statistical methods (23). We also assigned an additional score to each study according to its sample size as described in Cerin et al. (23). Each study was assigned the total assessment score (the sum of methodological quality and sample size scores), which was then used to assess the strength of evidence (detail explained below). The quality assessment tool with rationale for scores assigned to each item is described in Supporting Information (Table S2).

Assessing the Strength of Evidence

Conducting a traditional meta-analysis using models that include effect sizes of reported associations is difficult due to heterogeneities in environmental exposure measures between studies. An alternative meta-analysis method, known as *weighted Z-test* (33), was used to combine findings of multiple independent studies, and to assess the strength of the evidence. This approach has been used in recent reviews of the built environment and physical activity literature (23, 30). A conservative *z*-value was assigned to each reported relationship according to the level of significance (α) stated in the study (for statistically significant finding in the expected direction: z = 1.96 for α= 0.05 and z =1.64 for α= 0.10; z = 0.00 for null; for statistically significant findings in the unexpected direction: z = -1.96 for α= 0.05 and z = -1.64 for α= 0.10). Each reported finding was separately assessed according to the counting method described above. For a specific exposure-outcome relationship, a *weighted Z* value was calculated by summing *z* scores using the total assessment scores of the studies as *weights*, and dividing it by the square root of the sum of squared *weights*. The two-tailed *p*-value associated with the *weighted Z* value was then calculated, and used to determine the strength of the evidence using the following criteria: $p < 0.05$: weak evidence; $p < 0.01$: strong evidence; $p < 0.001$: very strong evidence (34). This meta-analytic approach was conducted only if a specific exposure-outcome relationship was reported five or more distinct times among the reviewed articles to meet the methodological standards for meta-analysis (35). If a specific relationship was reported four or less distinct times, it was considered insufficient to determine the strength of evidence. This meta-analytic approach, which accounts for the methodological quality of the study, quantifies the strength of evidence more accurately (in comparison to the approach of counting the number of significant associations) and provides a better assessment of the current evidence base (23).

RESULTS

The PRISMA flow diagram outlining the process of literature searching and article screening is provided in Figure 1. The initial systematic search across the eight databases produced 6,749 [3,402 unique] articles. After a sequence of independent assessment steps, 36 articles (36-71) were included in the review.

(INSERT FIGURE 1 ABOUT HERE)

Characteristics of Reviewed Studies

The data extracted from all the articles included in the meta-analysis are presented in Supporting Information (Table S3). Key characteristics of the articles are summarized in Table 1.

(INSERT TABLE 1 ABOUT HERE)

General study characteristics

More than one half of the articles were based on studies conducted in the United States (56%), followed by Canada (14%), Sweden (11%), and Australia (8%). Over 70% of the articles were published after 2013. With regard to geographical settings, most studies (78%) were conducted in urban areas only. The majority of studies recruited participants from multiple sites (38% from urban areas, 19% from both urban and rural areas). The sample sizes of the articles reviewed ranged from 262 to over 4 million. While the majority of articles used data collected in cohort studies (84%), six articles used data from national or state health registries, which were not primarily established for particular research purposes. The large-sample studies used such health registry data.

Research design aspects

Almost all the articles reviewed were based on observational studies. One natural-experimental study (37), which met our inclusion criteria (a longitudinal study on built environment and cardio-metabolic health), examined BMI changes among those who were assigned different residential locations (with little to no control over their neighborhood placement) after Hurricane Katrina. The follow-up duration ranged from less than 1 year to 18 years. In cohort studies, data were collected at two waves in about two fifths of the studies, while two studies collected data across seven waves. However, it should be noted that environmental attributes were measured only once in most studies (over 80%). Of these, a majority (n=23) used single time-point exposure measures that temporally matched with the study period (often at baseline), three used exposure data measured outside the study period, and three did not report the time point in which exposure data were collected. Seven studies used built environment attributes measured at multiple time-points concurrent with health data collection. About half of the articles (n=17) examined participants who did not relocate to a new address (stayers) during the study period. However, 11 of these appear to have assumed that participants did not relocate during follow-ups without checking their relocation status. About 10% of the articles focused only on those who relocated (movers), and one third of the articles included both stayers and movers in their sample.

<u>Outcomes</u>

Obesity outcomes (incidence of obesity, BMI, waist circumference, and body weight) were examined in 60% of the articles reviewed. Of the 17 articles using BMI measurements, nine used objectively-measured height and weight, and eight used self-reported measures. T2D outcomes (incidence of T2D, fasting glucose, HbA1c, HOMA-IR) were examined in a quarter of the articles. Hypertension outcomes (incidence of hypertension, systolic/diastolic blood pressure) were examined in 20% of the articles. CVD events (incidence of coronary heart disease or stroke or mortality due to CVD) were examined in 14% of the articles. All articles that examined outcomes related to T2D, hypertension, and CVD used objectively-collected data (i.e., measured by biomedical examination or retrieved from registry records), except two studies (49, 52) in which self-reported outcomes were used. Outcome variables were characterized as either changes in continuous measures (e.g., BMI change from baseline to follow-up) or incidences of adverse events (e.g., development of T2D at follow-up).

Exposures

A variety of built environment attributes were examined in the articles reviewed. Neighborhood walkability, a composite measure of environmental supportiveness for walking, consisting typically of objectively-measured residential density, street connectivity, and land use diversity (n=16) or using similar self-reported items measuring perceived environments (n=4), was the most frequently used exposure variable. Another frequently-examined exposure was the presence/proximity of neighborhood recreational facilities such as gyms and parks (n=13). Urban sprawl index, which is another composite measure, calculated similar to walkability but involving a degree of centering (concentration of population/employment within an area), was used in five studies. To synthesize findings in a succinct manner, other non-composite built environment attributes were classified into two categories: destinations and routes (25). In the current review, the destination category included presence/proximity of public transport stops and other local (community and retail) destinations. The route category included street connectivity, traffic intensity, perceived safety, and the amount of slope. Two articles (42, 54) included composite measures, which were constructed in ways that are different from walkability and urban sprawl indices. For example, *neighborhood development intensity* consisted of population density, road density, and resource (food, physical activity, and inactivity resources such as movie theaters) density (42).

The majority of articles used geographic information systems (GIS) to measure built environment attributes (n=33), while seven articles used perceived environmental characteristics (four studies used both). No audit measures were used in the articles identified. Of the studies using GIS measures, administrative units were the most frequently used area unit (n=15), followed by straight-line (circular) buffer areas around participant's residence (n=11), street-network buffer areas that can be reached within a certain distance from residence using street network (n=7), and distance measures (proximity of destinations from residence, n=7). Straight-line and street-network buffer sizes ranged from 400m to 3km. Five out of seven articles that used perceived environmental measures were from the Multi-Ethnic Study of Atherosclerosis (MESA) study. The MESA study asked participants to rate the suitability of the environment for physical activity (multiple items) within 1 mile or a 20-minute walk from home.

Analytical approaches

The statistical methods used varied widely according to data type, study characteristics, and research questions. For instance, statistical approaches included: modelling continuous outcome variables (linear regression models); modelling binary outcome variables (logistic regression models); modeling incidences of outcome events at follow-up (proportional hazard models); modelling within-person changes in exposures and outcomes by controlling for time-invariant confounders (fixed-effects models); and modelling concurrent trajectories of exposures and outcomes (latent growth models). Analysis accounted for area-level clustering through the use of multi-level regression models or robust (sandwich-type) standard errors. Studies adjusted for potential confounding factors including individual-level socio-demographic covariates (n=33); behavioral covariates (n=23); comorbid conditions (n=20); area-level socio-economic variables (n=23); and residential self-selection [directly by adjusting for preference or attitudinal measures (n=2), or by alternative approaches (n=9) such as use of fixed-effects models or propensity-score matching technique]. Two thirds of the studies examined effect modifications (n=24). Further details of analytical approaches used in the articles are provided in Supporting Information (Table S3)

Methodological quality assessment

Table 2 shows the summary of quality assessment. The full quality assessment results are provided in Supporting Information (Table S4). The highest possible quality score is 12.0. The mean (SD) quality score was 7.5 (1.1).

(INSERT TABLE 2 ABOUT HERE)

Summary of Findings

Table 3 presents the summary of findings for longitudinal relationships between built environment attributes and cardio-metabolic health outcomes. The table summarizes findings for each of which the relationship was reported five or more distinct times. The *Aggregated* columns list the number of significant findings (in the expected direction) of the total number reported, with corresponding percentage and number of articles that examined those relationships. The *Meta-analysis* columns list the *weighted Z-value* with the associated *p*-value calculated in the meta-analysis. The complete meta-analysis results are provided in Supporting Information (Table S5). In the following, we use the term "case" rather than "study" to describe a specific finding, as one study can examine many relevant relationships.

(INSERT TABLE 3 ABOUT HERE)

Walkability

Meta-analysis found strong evidence for longitudinal relationships of neighborhood walkability with obesity and T2D outcomes. Very strong evidence was found for the impact of walkability on hypertension. Other cardio-metabolic health outcomes (CVD, triglycerides, cholesterol, metabolic syndrome, C-reactive protein, dyslipidemia) were examined in a limited number of studies (<3 cases, not reported in Table 3). Studies employed different methods in constructing objectives measures of walkability (i.e., built environment attributes included, buffer type and size, composition method) (Table S3). The strength of the evidence for longitudinal relationships of objective walkability measures (i.e., excluding perceived measures) with obesity, T2D, and hypertension outcomes was attenuated, but remained significant. Perceived walkability was found to be consistently related with different health outcomes, including obesity outcomes (36, 39), T2D incidence (47), and hypertension incidence (55). However, there were insufficient cases to assess the strength of the evidence for perceived walkability measures alone.

Recreational facilities

Weak evidence was found for longitudinal relationships between neighborhood recreational facilities and obesity outcomes. Since most of the studies that examined recreational facilities as exposures did not provide explicit information on whether parks and other public open spaces (POS) were included or not, we combined them with the studies that focused on access to green spaces or parks. Meta-analysis found no evidence for longitudinal relationships between access to green spaces or parks and obesity outcomes. There were insufficient cases that examined relationships of neighborhood recreational facilities with T2D, hypertension, or CVD outcomes.

Urban sprawl

Meta-analysis found strong evidence for the impact of urban sprawl on obesity outcomes. Urban sprawl and walkability were both composite measures often constructed using similar components. A major difference between them is that walkability was measured within a smaller local area (e.g., census block in the USA, a buffer area around home), while urban sprawl was measured at a much larger scale such as counties or metropolitan statistical areas in the USA (37, 49, 58, 64), and included a degree of centering (72). No studies examined longitudinal relationships of urban sprawl with T2D or hypertension outcomes.

Destinations, routes and other composite measures

No evidence was found for longitudinal relationships of destinations (public transport stops, retail and community places), route attributes (street layout, amount of slope and traffic intensity), and other composite measures with obesity outcomes. There were insufficient cases that examined longitudinal relationships of these environmental measures with T2D, hypertension or CVD outcomes.

Mediation by physical activity and sedentary behavior

One fourth of the articles attempted to examine whether longitudinal relationships between built environment attributes and cardio-metabolic health outcomes were mediated by participants' physical activity (Table S3). However, almost of all of these studies tested the mediation effect simply by checking whether adjustment for physical activity (mostly with other potential mediators such as diet) attenuated the associations. This analytical approach is often ineffective to accurately estimate mediating effects (73). Thus, in the current review, the evidence for the mediating role of physical activity in the relationships examined is inconclusive, due to the limitation in analytical approaches. Nevertheless, one Australian study (71) tested the indirect effect of walkability on 10-year change in HbA_{1c} through self-reported physical activity using structural equation modelling, and found a partial mediation effect. None of the articles reviewed examined mediation by sedentary behavior.

Results stratified by relocation status

The studies reviewed can be categorized according to relocation status: stayers (reported); stayers (assumed); and movers. Table 4 shows the percentage of significant findings for each relocation status.

It was found that studies on stayers (particularly, on those who were confirmed to stay in the same location) had a higher percentage of significant findings, compared to the studies on movers.

(INSERT TABLE 4 ABOUT HERE)

DISCUSSION

Impact of Built Environment Attributes on Cardio-Metabolic Health

To our knowledge, this is the first systematic review of longitudinal studies that examined relationships between built environment attributes and cardio-metabolic health outcomes. Studies using longitudinal designs are recommended to better understand the potential causal effects of built environments on health outcomes (15, 17). Based on meta-analysis of existing longitudinal studies, this review found evidence suggesting causal relationships between living in a particular environment and change in cardio-metabolic health.

We found very strong evidence for the longitudinal relationships of walkability with hypertension outcomes. Strong evidence was found for the impact of walkability on obesity and T2D outcomes and for the impact of urban sprawl on obesity outcomes. A recent systematic review by Mackenbach et al. (15) reported inconsistent findings for the relationships between walkability and obesity outcomes, but consistent relationships between urban sprawl and obesity in North America. Another systematic review by Grasser et al. (13) also reported inconsistent findings for the relationships between walkability and obesity outcomes. However, these reviews mostly included cross-sectional studies and did not statistically assess the strength of the evidence using meta-analytical approaches that accounted for the methodological quality of the studies. Based on findings of the current review, it can be argued that living in more walkable and less-sprawled areas may provide residents with long-term benefits for cardio-metabolic health.

We found weak evidence for the relationships between neighborhood recreational facilities and obesity outcomes. This implies that, to some extent, having more places in the neighborhood to engage in moderate-to-vigorous physical activity may be protective against the development of obesity. No evidence was found for the relationships between access to green space or parks and obesity outcomes. This finding is in line with a previous systematic review of cross-sectional studies, which reported inconsistent findings for relationships between access to green space and obesity outcomes (74). It should be noted that studies on green spaces and cardiovascular health assuming a pathway other than physical activity (e.g., air quality, stress) were not included in the current review due to our inclusion criteria. Considering that researchers and practitioners consider POS as important and modifiable community resources that can contribute to resident's health (75), further longitudinal research on POS and health is warranted. It is known that the quality aspects of POS (size, features, and amenities) are relevant to residents' walking to and active use of POS (76). Research may need to incorporate the quality of POS to examine how they are associated with cardio-metabolic health.

Other environmental measures (destinations, routes, and other composite measures), for which we were able to synthesize findings, did not show any evidence of longitudinal relationships with obesity outcomes. Since the presence of local destinations is consistently associated with residents' walking (25, 77, 78), it was expected that residents of such locations would have lower risk of obesity. However, meta-analysis did not find any evidence for longitudinal relationships of access to local destinations with obesity outcomes. Since a large volume of walking (over 300 minutes/week) is needed to reduce obesity risk (79), walking to local proximate destinations may not be long enough. Several measures related to route aspects (street connectivity, traffic, safety, and slope) were combined to carry out meta-analysis in this review. We found no evidence for the combined impact of such route characteristics on obesity outcomes. This may be because these route attributes differed in their associations with cardio-metabolic health outcomes. For example, neighborhood traffic was found to be consistently associated with BMI increase (40), T2D incidence (52), and hypertension incidence (57), but neighborhood safety was not associated with T2D incidence (47) or hypertension incidence (55). This review found a relatively large number of studies examining composite environmental measures, such as walkability and urban sprawl. However, less research has been carried out on specific environmental attributes (such as residential density, street connectivity). There is a need for further longitudinal studies to identify specific built environment attributes that affect health outcomes to inform future urban design guidelines for new and established communities.

With regard to the outcome variables, obesity was still the most prevalent health outcome in this review (58%). However, the current review found that more than one third of the articles examined other cardio-metabolic health outcomes such as T2D and hypertension outcomes. Research in exercise science has shown that active lifestyle changes can be effective in reducing the risk of T2D and hypertension and can improve cardio-metabolic health profiles, even when there is no effective change in adiposity (80). This suggests that environmental attributes found to have weak or no evidence of longitudinal relationships with obesity (recreational facilities, POS, destinations, and routes) may be strongly or weakly related to T2D and hypertension outcomes. Future research needs to investigate about what aspects of built environments might be protective against broader cardio-metabolic diseases.

Issues on Research Design

Longitudinal studies of built environments involve either people who stayed in the same address (stayers) or those who relocated (movers). For studies on stayers, it is important to ensure that participants did not change their address during the study period. However, as shown in Table 1, many of the studies on stayers assumed that participants did not relocate or not explicitly reported about their relocation status. It is possible that the lower percentage of significant findings for assumed stayers (Table 4) may be due to the error introduced by including some participants who moved to a different neighborhood during the study period.

Examining environmental changes is considered to provide useful knowledge. In most cases, studies on stayers are unlikely to be suitable for examining environmental changes, as any changes in established neighborhoods are normally modest and slow. To better understand the health impact of significant environmental changes, research can use natural experiments (e.g., examining the effect of new transport infrastructure) or examine environmental changes among those who relocated. However, as shown in Table 4, the studies on movers had a lower percentage of significant findings compared to the studies on stayers. Some movers may have relocated not long before the follow-up measurement, thus may have had only a limited exposure to the new environment. To accurately examine the effects of environmental changes among movers, the time of relocation is needed to identify how long participants were exposed to the old and new environments, but only one study considered when during the study period participants relocated (44). This may be a reason for finding fewer significant results in the studies on movers.

Longer periods are considered beneficial for examining cardio-metabolic outcomes, since it takes time to develop these conditions (81). Data collection from multiple time points can be also advantageous, as it facilitates an examination of whether changes occurred consistently across time (82, 83). The majority of the studies had follow-up periods of five-years or longer, and many of these had data collection at three or more time-points. However, longer follow-ups may also incur higher and systematic attrition, which can cause bias in the estimates (84). A quantitative comparison on key characteristics of those who dropped out to those who remained in the study can be helpful to identify systematic attrition and to account for it. Another issue with a longer follow-up is that some environmental attributes can change over a long period of time (e.g., loss/addition of destinations, new residential development). However, less than 20% of the studies in this review measured environmental attributes at the same time with outcome measures. It is important that environmental attributes were measured at multiple points concurrent with health data collection, even for studies on stayers.

Built Environment Measurement Methods

Objective and perceived measures capture distinct aspects of the built environment (85). Mismatches between perceived and objectives measures of walkability attributes in the prospective relationships with BMI were reported previously (86). It was found that the strength of evidence for relationships between walkability and health outcomes was attenuated when the meta-analysis was restricted to objective measures of walkability, which suggests that perceived walkability may be more strongly related to health outcomes. It is possibly because of the match between participants' perceived local area and area where their daily behaviors take place. In contrast, objective walkability was assessed within a buffer area around the home or an administrative area, which may or may not match the area where participants' daily behaviors take place. Street-network buffers are considered as more likely to capture an accessible local area for residents, compared to alternative straight-line buffers or administrative units (87). However, less than a quarter of the studies reviewed employed street-network buffers. Similarly, buffer sizes also need to be appropriate for different types of attributes (e.g., public open space compared to utilitarian destinations) (32) and for different sub-groups (e.g., older adults compared to younger adults) (88). Not capturing local areas accurately in objective measures may have contributed to weakening the relevant evidence (89).

Residential Self-Selection

The relationship between built environment attributes and cardio-metabolic outcomes may be confounded by participants' self-selection of residential location (e.g., health conscious people chose to live in environments supportive of physical activity). If not appropriately adjusted, this may *magnify* the relationships between built environments and health outcomes (90). However, as shown in this review, cohort studies that are designed to collect health related data do not often measure participants' attitudes about or preferences for residential location. In the absence of self-selection data, alternative analytical approaches (i.e., propensity score matching, fixed effects models etc.) can be used (90) to address confounding due to residential self-selection as was done in some reviewed studies (43, 44, 46, 49, 52-54, 67, 68).

Mediation by Physical Activity

We postulated in this review that the relationships between built environment attributes and cardio-metabolic health outcomes are partly mediated by physical activity. However, we did not find conclusive evidence for mediation by physical activity, mainly due to limitations in traditional statistical mediation analysis that has been shown to provide incorrect findings (91). For example, traditional methods require that the total effect of an exposure on an outcome must be non-zero and larger than the direct effect, to observe a significant indirect effect. However, recent statistical mediation analysis literature argue that it is possible to have a non-significant total effect, yet a significant indirect effect (i.e., when multiple mediating pathways exist and cancel out each other) (92). In relationships between built environment exposures and cardio-metabolic health outcomes, it is hypothesized that multiple mediating pathways exist (e.g., physical activity, dietary behaviors, air pollution) (9). Thus, care must be taken to disentangle the individual mediating mechanisms. In addition, when estimating the total effect of an exposure on an outcome, inappropriate adjustment for intermediate behavioral variables may lead to *overadjustment* and can produce incorrect null findings (93). Further, despite some increased attention in recent years to understand environmental correlates of sedentary behavior, and the health impacts of daily sedentary behavior such as TV viewing and car driving (94, 95); no studies have examined how this behavior is involved in longitudinal relationships between built environments and cardio-metabolic health. To better understand how environmental attributes influence residents' health, future studies need to examine the role of multiple potential behaviors using the recent developments in mediation analysis methods (73)

Strengths and Limitations

The present systematic review has several strengths. We exclusively reviewed longitudinal studies by systematically searching eight databases. We assessed the methodological quality of the articles using a quality assessment tool that accounted for methodological issues including study design, measurement, and analysis, and synthesized the evidence using meta-analysis. One of the limitations of this study is that the quality assessment tool, which was adapted from Cerin et al. (23), was extended mainly using inputs from the co-authors. A Delphi study aiming to obtain consensus among experts about key criteria for assessing quality in built environment and health studies can produce a more robust synthesis of the literature in future systematic reviews. We grouped exposure variables to succinctly summarize current knowledge. However, the reviewed studies varied in how environmental attributes were measured, and that variation may have influenced the summary findings shown in Table 3. In particular, the studies differed in calculating the composite index of walkability. Future research can explore further how different walkability indices are associated with health outcomes, to produce composite environmental measures that can better predict long-term impacts on cardio-metabolic health. This review focused on studies that examined the health impact of areas where participants resided, typically using a buffer or an administrative area around participant's residence. However, it is possible that environment outside such areas may also affect health. Future research/review can investigate the health impact of other specific environments, such as workplace (and its vicinity) and access to a regional center. We may have missed some studies on greenness and cardio-metabolic health, because diverse research fields, using terms that were not included in search terms of this review (e.g., vegetation, land cover, forest), have investigated this topic. The presence of multiple pathways between greenspace and health made it difficult for this review to include all the studies on this topic in a realistic manner. A future review, focusing on greenspace yet incorporating multiple pathways, is needed to better understand the overall health benefits of greenspace. Most of the studies reviewed were conducted in a limited number of Western countries, which limits the generalizability of the findings to non-Western countries and to other developed/developing countries. Considering that developing counties may experience greater environmental changes in a shorter timeframe, further longitudinal studies from various parts of the world are needed.

CONCLUSION

The systematic review with meta-analysis of longitudinal studies found that living in more walkable and less-sprawled areas is likely to have protective effects against the development of obesity, T2D, and hypertension. Future longitudinal studies need to examine relationships of specific attributes of built environments with a range of cardio-metabolic outcomes including T2D, hypertension, and CVD. Research on behavioral mechanisms is also warranted to identify underlying behaviors involved in relationships between built environments and cardio-metabolic health.

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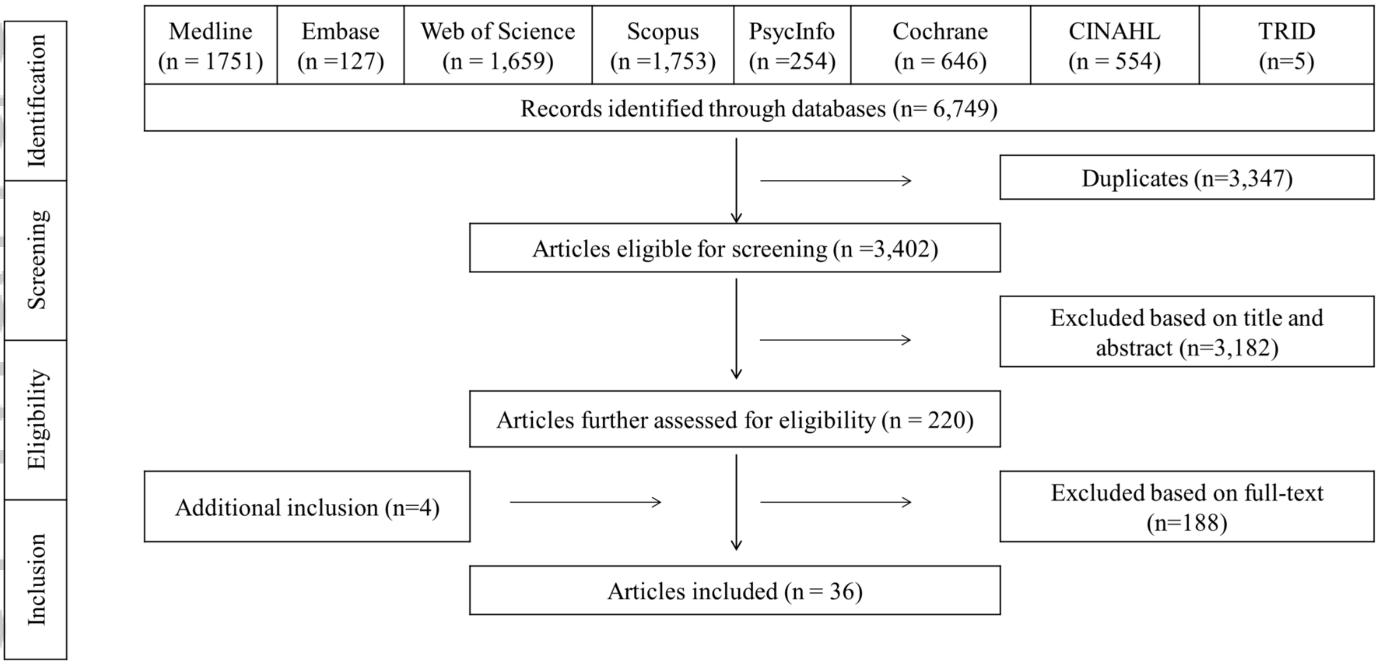

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