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International comparisons of the associations between objective measures of the built environment and transport-related walking and cycling: IPEN Adult Study

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Abstract

Introduction—Mounting evidence documents the importance of urban form for active travel, but international studies could strengthen the evidence. The aim of the study was to document the strength, shape, and generalizability of relations of objectively measured built environment variables with transport-related walking and cycling.

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Methods—This cross-sectional study maximized variation of environments and demographics by including multiple countries and by selecting adult participants living in neighborhoods based on higher and lower classifications of objectively measured walkability and socioeconomic status. Analyses were conducted on 12,181 adults aged 18–66 years, drawn from 14 cities across 10 countries worldwide. Frequency of transport-related walking and cycling over the last seven days was assessed by questionnaire and four objectively measured built environment variables were calculated. Associations of built environment variables with transport-related walking and cycling variables were estimated using generalized additive mixed models, and were tested for curvilinearity and study site moderation.

Results—We found positive associations of walking for transport with all the environmental attributes, but also found that the relationships was only linear for land use mix, but not for residential density, intersection density, and the number of parks. Our findings suggest that there may be optimum values in these attributes, beyond which higher densities or number of parks could have minor or even negative impact. Cycling for transport was associated linearly with residential density, intersection density (only for any cycling), and land use mix, but not with the number of parks.

Conclusion—Across 14 diverse cities and countries, living in more densely populated areas, having a well-connected street network, more diverse land uses, and having more parks were positively associated with transport-related walking and/or cycling. Except for land-use-mix, all built environment variables had curvilinear relationships with walking, with a plateau in the relationship at higher levels of the scales.

Keywords

walking; cycling; transport; built environment; international; IPEN

1 Introduction

Engaging in transport-related walking and cycling (i.e. active travel) has the potential to reduce the risk of non-communicable diseases, air pollution and traffic congestion and at the same time contribute to more livable and sustainable cities (Beaglehole et al.; Gehl, 2010; Sallis et al., 2012). Urban planning in conjunction with supportive transportation policies is crucial in the effort to promote active travel. One strategy is creating safe spaces, places and destinations designed for pedestrians and cyclists. However, the evidence of the role of built environments in active travel has been inconsistent, and studies with comparable and objective methods across countries are requested to better inform policy makers about environmental strategies for increasing active transport (Bauman et al., 2012).

Cervero and Kockelman (1997) highlighted the 3Ds (density, diversity and design) as potential built environment levers to increase active travel modes. The 3Ds have since been examined and their operationalization refined in a large number of studies (Ewing and Cervero, 2010; Heinen et al., 2009; Lee and Moudon, 2006; Saelens and Handy, 2008). Residential density has been shown to be almost linearly associated with walking for transport; however, the relationship with cycling might be of less importance (Forsyth and Krizek, 2010; Kerr, 2015). A diverse mix of different land-uses in the neighborhood and destinations within reachable distances has also been shown to be associated with more walking and cycling for transport (Durand et al., 2011; Heinen et al., 2009; McCormack and Shiell, 2011). A grid-pattern street design increases the permeability of the city, decreases distance to destinations, and provides numerous alternate routes to pedestrians and cyclists (Witten et al., 2012). Another design variable at the urban form level is the availability of urban green spaces, which can give pedestrians and cyclists a more pleasant, and in some cases a safer, experience when moving through the city. However, the results for public open space and active travel research remains mixed with further investigation required (Koohsari et al., 2015).

The majority of built environment and active travel research relies on cross-sectional studies based on nation- or city-specific data, and many of them also use self-reported perceptions of the environmental variables. This creates uncertainty for whether the observed associations are causal or generated by other confounding factors, such as self-selection (Christiansen et al., 2014; Eid et al., 2008). Natural experiments to enhance evidence of causality are difficult to implement within this field (Ding and Gebel, 2012; McCormack and Shiell, 2011). An alternative is to investigate built and social environments in different geographical settings. Besides increasing variation of the built environment (Adams et al., 2014), it also offers the opportunity to investigate heterogeneity in associations across sites. Such a cross-national comparable research agenda has been formed through the International Physical Activity Network (IPEN). The purpose of IPEN was to explore the association between physical activity behaviors and a broad array of built and social environment features. The IPEN Adult study has a common research design and generally comparable measures for both physical activity and objective built environment variables across 12 countries (Adams et al., 2014; Kerr et al., 2013).

The aim of the present study was to pool international data from 14 cities in 10 countries, and to document the strength, shape, and generalizability of the relation of objectively measured built environment variables with transport-related walking and cycling. To our knowledge, no study has to date used comparable spatial measures applied internationally with absolute scales to examine generalizability of dose-response relations with active travel. If associations and shapes of associations are found to be similar across most cities, they will provide a starting place for developing international criteria for built environment recommendations to promote transport-related walking and cycling. In the case of associations differing across countries, strategies developed at national- or city-levels can be recommended.

2 Methods

2.1 Recruitment and participants

The IPEN Adult study design has been described in detail elsewhere (Kerr et al., 2013). Briefly, the study was cross-sectional and designed to maximize variation within the sample by selecting adult participants in multiple countries living in neighborhoods based on higher and lower classifications of objectively measured walkability and socioeconomic status. For every administrative unit in each city a walkability index score was calculated as a function of at least two of the following variables: net residential density, land use mix, intersection density, and the retail floor-area-ratio (Adams et al., 2014; Frank et al., 2010; Kerr et al., 2013). Area-level socioeconomic status was also derived, usually based on census data. Neighborhoods were classified into four types for recruitment purposes: higher walkability-higher socioeconomic status, higher walkability-lower socioeconomic status, lower walkability-higher socioeconomic status and lower walkability-lower socioeconomic status.

The total IPEN Adult sample consisted of 14,222 adults aged 18–66 years, sampled from 17 cities across 12 countries. However, three cities did not collect either objective built environment data or the International Physical Activity Questionnaire transport-related items (IPAQ-long form) (Pamplona, Spain; Hong Kong, China; and one of the two cities from Czech Republic). Thus, the cities and countries included in this analysis were: Adelaide, Australia (AUS); Ghent, Belgium (BEL); Curitiba, Brazil (BRA); Bogota, Colombia (COL); Olomouc, Czech Republic (CZ); Aarhus, Denmark (DEN); Cuernavaca, Mexico (MEX), Christchurch, North Shore, Waitakere, and Wellington, New Zealand (NZ), Stoke-on-Trent, United Kingdom (UK) and Baltimore and Seattle, United States (US) with a total sample size of 12,181 participants. Forty-three percent of participants were male, 59.7% married or living with a partner, 74.7% had a job or unpaid work outside home, and 43.3% held a tertiary education. The distributions of socio-demographic characteristics were similar across study sites and have been reported elsewhere (Kerr et al., 2013). Each country obtained ethical approval from their local institutions as well as San Diego State University, and all participants provided informed consent.

2.2 Outcome variables

Relevant IPAQ-long form items were used to assess the frequency of walking and cycling for transport. Participants were asked to report the number of days during the last seven days they walked or cycled for at least 10 minutes to get from place to place. Dichotomous outcome measures were computed to represent any walking or cycling for transport during the last week that lasted for at least 10 minutes (no, yes). The total days in the last week spent walking or cycling for at least 10 minutes were also used as outcome variables (1–7days).

2.3 Environmental variables

For each participant two street-network buffer sizes (500 m and 1 km) were created around their residential address, and four objectively-measured built environment variables were calculated. These variables were: net residential density (number of dwellings per km^2 of buffer areas devoted to residential use), land-use mix (entropy score of three land-uses: residential, retail and civic), street connectivity (number of intersections with three or more intersecting road segments per km^2, and parks (number of parks intersecting participant buffers). These variables were selected based on their relevance to transport-related walking and cycling, while being limited by the availability of variables and comparability across participating cities. A description of GIS data collection, comparability and scoring methods can be found in Adams et al. (2014).

2.4 Socio-demographic covariates

Self-report questionnaire data was used to assess following covariates: age (years), sex (male, female), marital status (living with a partner, single), educational attainment (college graduate, not college graduate), employment status (employed, unemployed).

2.4 Data Analytic Plan

Descriptive statistics for the four outcome variables (any, and total days of transport-related walking and cycling) were computed for the whole sample and by city. Associations of objectively measured built environment variables with transport-related walking and cycling were estimated using generalized additive mixed models (GAMMs)(Cerin et al., 2014; Wood, 2006). GAMMs can accommodate positively skewed continuous, count as well as dichotomous outcomes, account for dependency in error terms due to clustering (participants recruited from selected administrative units), and estimate complex dose-response relationships (Wood, 2006). GAMMs with binomial variance and logit link functions were estimated for any walking and any cycling in the last week (dichotomous outcomes. The antilogarithm of the regression coefficient estimates of these GAMMs represents odds ratios. GAMMs with negative binomial variance and logarithmic link functions were used to model non-zero days per week of walking or cycling (count variables). The antilogarithms of the regression coefficient estimates of the GAMMs based negative binomial variance functions represent the proportional difference in outcomes associated with a unit difference in the correlates. For all GAMMs, random intercepts were specified to account for clustering effects at the administrative unit level.

Main-effect GAMMs estimated the dose-response relationships of all built environment attributes with the active travel outcomes adjusting for city (in the form of dummy variables), socio-demographic covariates, and administrative-unit-level socio-economic status. Covariate-adjusted single-environment-variable and multi-environment-variable (including all buffer-specific environment variables independently contributing to a specific outcome) GAMMs were estimated. Multiple built environment variables could be simultaneously entered in GAMMs, as collinearity was not identified as being problematic (variance inflation factor<2). Curvilinear relationships of built environment attributes with active travel outcomes were estimated using thin-plate spline smooth terms in GAMMs (Wood, 2006). Smooth terms failing to provide sufficient evidence of a curvilinear relationship (≥10 difference in AIC)(Burnham and Anderson, 2002) were replaced by simpler linear terms. Separate GAMMs were generated to estimate built environment attributes by city interaction effects to test for heterogeneity in associations across sites. The significance of interaction effects was evaluated by comparing AIC values of models with and without a specific interaction term (≥10 difference in AIC)(Burnham and Anderson, 2002). Significant interaction effects were probed by computing site-specific associations. Of the eligible sample on 12,181 participants, only 4.2% (n=507) of cases had missing data on at least one of the examined variables; analyses were performed on complete cases (n=11,674). Participants with incomplete data were more likely to be older (p=0.017), unemployed (p=0.030) and with lower educational attainment (p=0.04). The likelihood of having missing data was unrelated to build environment and active travel variables. All analyses were conducted in R (R Development Core Team, 2011) using packages 'mgcv'

(Wood, 2006), 'gamm4' (Wood and Scheipl, 2014), 'car' (Fox and Weisberg, 2011), and 'gmodels' (Warnes, 2014).

3 Results

3.1 Descriptive statistics

Table 1 shows descriptive statistics for the four transport-related walking and cycling outcomes for the whole sample and each of the 14 cities (complete data set only). The percentage of participants reporting any walking for transport in the last week ranged from 52.1% in Ghent (BEL) to 90.3% in both Bogota (COL) and Cuernavaca (MEX). The average days walked for transport during the last week ranged from 2.0 in Christchurch (NZ) and Ghent (BEL) to 4.8 in Bogota (COL). The percentage of participants reporting any cycling for transport in the last seven days was substantially lower than walking, and ranged from 1.3% in Cuernavaca (MEX) to 61.6% in Aarhus (DEN). The mean weekly days cycled were less than 1 for all locations with the exception of Ghent (BEL) and Aarhus (DEN) at 1.7 and 2.4 days, respectively.

The individual measure of each participant's neighborhood characteristics measured at 500 m and 1 km street network buffers showed great variation between and within cities, which have been presented elsewhere (Adams et al., 2014). For the current sample the median and interquartile-range of the four built environment variables for the 500 m buffer are presented in Table 2 (see Appendix for details of distribution for both buffer sizes). The median net residential density across all sites was 2,617 dwellings per km^2, and highest in Olomouc (CZE) with 15,326 dwellings, and lowest in Christchurch (NZ) with 1,534 dwellings. There was considerable within-city variation from very low residential densities to higher densities, and across continents the European and Latin American sites had generally higher densities than the American and Oceanian sites. The entropy score for the mix of three land-uses reveal large within-city variation from single land-use (score=0) to an even split between residential, retail and civic land-use (score=1). Aarhus (DEN) had the highest median entropy score of 0.81, while Waitakere (NZ) and Christchurch (NZ) had the lowest median scores of 0.11 and 0.12, respectively. Regarding street connectivity there was an almost continental gradient with the Latin American cities being the most connected followed by Europe, US, Australian, and New Zealand sites. Bogota (COL) and the Australasia cities had the most parks intersecting the participant buffers.

3.2 Associations of built environment attributes with any walking for transport

All built environment attributes were positively linearly associated with the odds of engaging in any bout (≥10 min) of walking for transport in the single-environment-variable models (Table 2). This was also the case in the multi-environment-variable models, except for intersection density (1 km) and number of parks (500 m). Curvilinear relationships were observed between the odds of engaging in any walking for transport and net residential density, intersection density, and number of parks (Table 2). The odds of walking was positively associated with residential density up to 12,000 dwellings/km^2 but negatively thereafter for the 500 m buffer (Table 2). The odds of walking for transport was positively related to intersection density up to values of 200–250 intersections/km^2 and negatively thereafter. A positive gradient in the odds of walking for transport was observed for the number of parks up to 8–10 parks/km^2, while a negative gradient in the odds was found for those with more than 20–25 parks/km^2 for the 1 km residential buffer.

Three of the four built environment attributes showed significant city interaction effects on the odds of engaging in any walking for transport (Table 2). Specifically, significant associations were observed in the single- and multiple-environment-variable models between net residential density (1,000 dwellings/km^2; 1km buffer) and the odds of walking for transport in Adelaide (AUS) (OR=1.36; 95% CI: 1.19, 1.55; p<0.001), Ghent (BEL) (OR=1.15; 95% CI: 1.12, 1.18; p<0.001), Aarhus (DEN) (OR=1.08; 95% CI: 1.03, 1.13; p=0.003), Seattle (USA) (OR=1.27; 95% CI: 1.15, 1.39; p<0.001), and Baltimore (USA) (OR=1.24; 95% CI: 1.11, 1.39; p<0.001), but not in the remaining nine cities (single-environment-variable estimates reported). Land use mix within 1 km buffers was related to the odds of walking in Ghent (BEL) (OR=4.83; 95% CI: 1.64, 14.25; p<0.001), Wellington (NZ) (OR=5.11; 95% CI: 1.40, 18.68; p<0.001), and Seattle (USA) (OR=2.10; 95% CI: 1.06, 4.17; p=0.003), while for land use mix within 500 m buffers significant associations were found in Ghent (BEL) (OR=3.72; 95% CI: 1.98, 7.00; p<0.001) and Seattle (USA) (OR=2.70; 95% CI: 1.52, 4.77; p<0.001) only. The latter interaction effect (500 m) was not significant in the multiple-environment variable model. In the single-environment-variable models number of parks (1 park/km^2; 500 m buffer) was positively related to the odds of walking for transport in Ghent (BEL) (OR=1.37; 95% CI: 1.18, 1.59; p<0.001), Aarhus (DEN) (OR=1.22; 95% CI: 1.01, 1.49; p=0.044), and Seattle (USA) (OR=1.38; 95% CI: 1.19, 1.59; p<0.001) only. Yet, this interaction effect was not significant in the multi-environment-variable model.

3.3 Associations of built environment attributes with days of walking for transportation

All built environment attributes were associated with non-zero days/week of walking for transport (Table 3) in the single-environment-variable models. Net residential density, intersection density, and number of parks remained significant predictors of non-zero days/week of walking for transport in the multi-environment-variable models, and curvilinear relationships were observed (Table 3). The dose-response relationships for intersection density and number of parks were similar to those observed for the odds of *any* walking for transport (see above). Values of residential density ranging from 0 to 7500 dwellings/km^2 were associated with the largest increases in non-zero days/week of walking (Table 3).

Intersection density and number of parks showed significant study site interaction effects with days of walking for transport (Table 3). City site moderated the associations of intersection density (100 intersections/km^2; 1 km buffer) with non-zero days/week of walking for transport in the single-environment-variable model. Significant associations were found in five cities only. These were Adelaide (AUS) (e^b=1.17; 95% CI: 1.04, 1.32; p=0.011), Ghent (BEL) (e^b=1.23; 95% CI: 1.13, 1.33; p<0.001), Aarhus (DEN) (e^b=1.37; 95% CI: 1.07, 1.75; p=0.013), Wellington (NZ) (e^b=2.23; 95% CI: 1.51, 3.29; p<0.001), and Seattle (USA) (e^b=1.45; 95% CI: 1.19, 1.76; p<0.001). City was a moderator of the associations between number of parks (1 park/km^2; 1 km buffer) and non-zero days/week of walking for transport in both single- and multi-variable models. Significant positive associations were found in Ghent (BEL) (e^b=1.47; 95% CI: 1.27, 1.69; p<0.001), Aarhus (DEN) (e^b=1.35; 95% CI: 1.13, 1.60; p<0.001), North Shore (e^b=1.12; 95% CI: 1.00, 1.24; p=0.045), Waitakere (NZ) (e^b=1.22; 95% CI: 1.03, 1.43; p=0.019) and Seattle (USA) (e^b=1.26; 95% CI: 1.07, 1.49; p=0.005).

3.4 Associations of built environment attributes with any transport-related cycling and number of days with transport-related cycling

Net residential density, intersection density, and land use mix were positively associated with the odds of engaging in any bouts (≥10 min) of cycling for transport in the last week (Table 4). Only intersection density and land use mix remained significantly associated in the multi-environment-variable models. No curvilinear relationships were found.

Cities moderated the associations of number of parks with the odds of engaging in any bout of cycling for transport. Specifically, the number of parks (1 park/km^2; 500 m buffer) were positively associated with the odds of any cycling for transport in Ghent (BEL) (OR=1.20; 95% CI: 1.05, 1.37; p=0.009), Aarhus (DEN) (OR=1.24; 95% CI: 1.06, 1.46; p=0.008) and Seattle (USA) (OR=1.34; 95% CI: 1.12, 1.59; p=0.001) only. This interaction effect remained significant in the multi-environment-variable models.

Residential density and land use mix were linearly positively associated with days per week of cycling for transport (Table 4). Yet, after adjustment for other built environment attributes, only land use mix remained a significant predictor of this outcome. No curvilinear relationships or interaction effects by study site were observed for number of days of cycling for transport.

4. Discussion

The aim of the study was to examine the strength, shape, and between-city differences of relations between objectively-measured built environment variables and transport-related walking and cycling across multiple cities and countries. We found positive associations for walking for transport with all the environmental attributes, but also found that the relationships were not linear for residential density, intersection density, and the number of parks. Our findings suggest that there may be optimum values for these attributes, beyond which higher densities or number of parks could have a negative impact. Cycling for transport was associated linearly with residential density, intersection density (only for any cycling) and land use mix, but not with the number of parks. The detailed analyses of the associations between active travel behavior and built environment characteristics are separated and discussed by four themes: the dense city, the mixed city, the connected city, and the green city.

4.1 The dense city

Residential density showed a positive curvilinear association with walking for transport. This was found for both the odds of any and the number of days walked for transport. Furthermore, associations were found for both 500 m and 1 km buffer sizes, and after adjusting for the other built environment variables. For the association with any walking the associations appeared to be stronger for the 500 m buffer; significant only for the American, two of the European and the Australian cities using the 1 km buffer. The association with cycling for transport was weaker, and significant only in the single built environment variable models.

Besides confirming previous findings of a positive association between residential density and walking for transport, this study contributes evidence of a threshold, showing a gradient that plateaus. The threshold for the odds of any walking for transport was approximately 12,000 dwellings per km^2 and 7,500 dwellings per km^2 for odds of days walked for transport based on 500 m buffers for environmental measures. These thresholds were objectively-measured and comparable across sites and could therefore serve as meaningful maximum point for future built environment densifications. However, this level of residential density is not typically available for most participating cities, except for some European and Latin American cities (Table 2). This means that increasing residential density may be recommended to facilitate more walking in North American (excluding Mexico) and Australasian cities (without considering a higher limit), but may not have to be promoted in some areas of the European and Latin American cities.

An additional 1,000 dwelling/km^2 was associated with a 3 times higher likelihood of any walking bouts and a 10 % increase in days of walking (500 m buffer, MEV). A crude city level comparison suggests a positive association was also evident, as cities with the highest residential densities (i.e. Olomouch (CZ) and Bogota (COL)) also had the highest average of days with walking for transport (i.e. 4.6 and 4.8 days, respectively), and among the four New Zealand cities, Wellington had twice as high residential density and nearly twice as many days of walking for transport than the three other New Zealand sites.

Residential density was not found to be consistently associated with cycling in current analyses using objective built environment exposures. The weak association between objectively measured residential density and cycling for transport in the single environment model became non-significant in the multiple environment models. Crude city comparisons showed the three European cities (Aarhus (DEN), Ghent (BEL) and Olomouc (CZ)), which had high levels of residential density, also had the highest proportion of cycling for transport. However, Christchurch (NZ) had very low residential density, but comparatively high rates of cycling for transport. Christchurch had the lowest mean residential density of all cities at only 1,683 dwelling per km^2, but the highest proportion of weekly cycling outside of Europe (17.5% reported any cycling for transport during the last week). Christchurch's high level of cycling can potentially be explained by a flat terrain and local policies to promote cycling. The city promotes cycling and has been nicknamed 'Cyclopolis' (Kennett et al., 2004). Consequently, cycling has been considered in local planning policies for decades, resulting in a comprehensive cycling strategy incorporating cycling infrastructure, education, and policies (Christchurch City Council, 2012).

4.2 The mixed city

A city with high levels of mixed use affords short distances to multiple types of destinations, making active transport more attractive and feasible. We found positive associations between land-use-mix and any bouts of walking and cycling for transport in both single- and multi-environment-variable models. For instance, compared to participants in areas with a single land use (residential), those living in areas with the equal proportion of residential, retail, and civic uses were 1.5 times more likely to walk for transport (500 m buffer, MEV). There was no moderation of effect for the 500 m buffer in the multiple-environment-variable model, which supports a generalizable association across cities. However, at the 1 km buffer, the associations were only significant in Ghent (BEL), Wellington (NZ) and Seattle (US). Interestingly, land-use-mix was associated with both any cycling and with more days of cycling for transport. In fact, land-use-mix was the only built environment variable remaining significant in the multi-environment-variable model for non-zero days of cycling for transport. There is little doubt that a mix of land-use supports active transport, but Durand et al. (2011) pose the relevant question about how best to quantify higher and lower mixed uses. The entropy measure in the current study used three different objective measures of land uses. The score would be 1.00 if there was an even distribution between the three land-uses. This might be the reason for not finding any threshold values (curvilinear relationships), as for example higher counts of retail than the two other land-uses will result in a lower score than the equilibrium. On one hand, such an entropy index is replicable across a variety of countries and thus available to city planners, but does not give easily interpretable thresholds or an understanding of what mix is optimal for policy makers to utilize.

On the other hand, our results, were consistent with multiple reviews (Durand et al., 2011; Heinen et al., 2009; Owen et al., 2004; Sallis et al., 2012; Van Holle et al., 2012) that show positive associations between land use mix and walking. Future research should attempt to unpack which destinations are critical for active transport, and which are less important. This will improve the interpretability for policy-makers and planners in terms of understanding the types of destinations needed to create an environment that supports transport-related walking and cycling.

4.3 The connected city

A connected city has several potential pathways to increase transport-related walking and cycling. It can decrease travel time as a more direct route can be available in well-connected street network, and traffic volume may be more evenly dispersed, which may provide pedestrians and cyclists opportunities to travel on streets with less traffic away from arterial roads. A curvilinear relationship was found between intersection density for both measures of walking for transport, showing a positive association up to 200–250 intersections per km^2, which is the case for most places except for the most densely connected neighborhoods in Bogota (COL) and Cuernavaca (MEX). Any bouts of cycling for transport were significantly associated with intersection density in both the single- and multi-environment-variable models. The effect for any cycling was approximately an odds ratio of 1.3 per 100 intersections/km^2. Based on our data, many cities would need a relative large increase in number of intersections to influence the uptake of cycling for transport.

Other studies also highlighted intersections as an indicator of a walkable city, and made a distinction between connectivity for cars and for walkers and cyclists (Ewing and Cervero, 2010). Retrofitting pedestrian links between cul-de-sac layouts can increase connectivity, and these are beginning to gain popularity in some cities. This strategy increases accessibility for those using active travel modes and decreases it for those traveling by cars (Cao et al., 2006).

4.4 The green city

The presence of greenery, street trees, parks and green corridors make walking and cycling trips more pleasant, with research showing cyclists are willing to make a detour for a greener route (Krenn et al., 2014). Research on the association between city parks and active transport remains less extensive than that on other built environment characteristics. However Kaczynski and Henderson (2007) found several studies confirming this association with transport behaviors. Keeping in mind that parks are consistently associated with recreational walking, the current study gives only limited support to increasing green areas as a strategy to increase active travel. No overall associations were observed for parks and transport-related cycling, and the association with days of walking for transport was curvilinear, very modest and only significant for five sites. The association with any walking was stronger up to 10 parks/km^2, as the odds ratio increased from approximately 2.5 to 3.5 from 0 to 10 parks, respectively.

We found that city significantly moderated the effect between parks and cycling, as the number of parks was associated with higher odds of cycling only in Ghent (BEL), Aarhus (DEN) and Seattle (US) – both in the single- and multiple-environment models. A reason for the effect in these cities could be due to an integrated approach using green areas as transport corridors for cycling to connect with other cycling infrastructure (Seattle Department of Transportation, 2007; Aarhus Kommune, 2007). In other countries investigated, cycling is prohibited in many parks. These cities had among the highest cycling rates, so most cities had very limited power to detect associations with cycling. Our limited findings could be explained by the number of parks being insufficient to operationalize a potential effect. Research has shown that park characteristics and size are very important for recreational park use (Kaczynski et al., 2008; Lee and Maheswaran, 2011), and that the connectedness of green areas in green transport corridors could be an attractive and safe option for active travel (Krenn et al., 2014). Finally, the location of parks also plays an important role for active travel, as there needs to be local destinations to travel to.

4.5 Generalizability across study sites and buffer sizes

Even though we found overall associations between the built environment and active travel, several between-city differences in associations were observed, especially for the 1 km buffer measures. The reasons for these differences across cities could be explained by unmeasured confounders, micro-scale factors in the environment or differences in culture. These could include aesthetics, safety from crime, traffic safety, cycling and pedestrian facilities and car ownership. Notably, significant positive associations were only found in Europe (Ghent and Aarhus), US (Baltimore and Seattle) and Australasia (Adelaide, Wellington, North Shore, Waitakere), but not in the three study sites in Latin America. Previous research has raised doubts about the transferability of walkability-related variables in a Latin American context (Cervero et al., 2009; Salvo et al., 2014b). Present city-specific findings could also be interpreted as a difference between developed and developing cities, city planning policies, and automobile ownership. Cervero (2009) hypothesized that the lack of variability in dense and mixed city planning in Bogota was the reason for not finding an association with urban form characteristics. They found instead support for the role of cycling facilities (e.g. street density and bike lane connectedness). Specifically in Latin American cities, such as Bogota and Cuernavaca, car ownership remains low in comparison with cities of high income countries. In these cases, walking for transport may be more reflective of need rather than choice since a significant proportion of the population walks because they have no other option for transportation (Salvo et al., 2014a).

Buffer size is an ongoing discussion in neighborhood-based spatial research (Kwan, 2012). We used individual street-network buffers at 500 m and 1 km, which was an available and comparable measure across all cities. Some associations tended to be stronger at the 500 m buffer for walking, and the 1 km buffer was more often associated with city moderation effects. Associations between the built environment and transport-related cycling tended to be stronger using the 1 km buffer, which supposedly could be explained by the larger distances travelled by cycling. Only land-use-mix and intersection density were significantly associated with cycling for transport. We suggest that future research further investigate appropriate buffer sizes for cycling, relevant infrastructure, hilliness and the allocation of street space for motorized transport compared to cycling.

4.6 Limitations

The study presented analyses based on objective measures of the built environment, which were judged to be generally comparable across countries (Adams et al., 2014). However, there were several uncertainties when comparing objective built environment variables across different cities, as not all countries were able to capture and collect the same types of spatial information. The use of 500 m and 1 km street-network buffers to assess the neighborhood environment of the participants can also be disputed, as adult participants often have much larger range when undertaking daily activities (Ivory et al., 2015). On the other hand the positive associations found in this and other studies support the use of street-network buffers. The effects for walking tended to be more consistent for the 500 m buffer across cities, and the association appeared stronger for cycling in the 1 km buffer. There is some evidence that an environment supportive for walking versus cycling may be somewhat inconsistent. In one study favorable conditions for walking - i.e. many destinations within 500 m – had a negative association with cycling in Denmark (Nielsen et al., 2013). Even though, there are several similarities between transport-related walking and cycling for transport and the overall need for destinations, designated space and safe routes, future studies should look into special cycling facilities, networks and protected cycleways.

The active travel measure relied on self-report in the IPAQ, and used the number of days with bouts of more than 10 minutes of a given transport mode as dependent variable. As this was a self-report measure, recall bias and social-desirability bias may have occurred. Furthermore, for complexity reasons we chose not to include total minutes of walking or cycling for transport, and the findings can therefore not be used a guidance for increasing total time of transport-related physical activity, but only the presence and frequency of the active travel modes. In addition we did not control for car ownership which could explain in part high prevalence of walking behaviors in Colombia and Cuernavaca, where car ownership remains low compared to other cities (Salvo et al., 2014a). Finally, the set of cities that were included in the study is not representative of the five continents we studied. Future studies would need to expand the investigation to a larger number of cities that are more representative of the entire global population of cities. This would allow modelling cities as a random factor and the data would yield more robust estimates of dose-response relationships.

5 Conclusion

Across culturally and geographically different countries and cities, our study underscores the importance of density, land-use mix, parks and street connectivity for supporting active travel in adults. The study adds some interesting new findings. First, a threshold effect of residential density on walking for transport was found, where no additional benefits were found above 12,000 dwellings per km^2; residential density did not have a significant effect on cycling for transport; and built environment attributes may be more important in cities located in developed countries. Second, both land-use mix and street connectivity were important for both walking and cycling for transport. Third, there was variation across sites how parks were related to active transport, and especially for cycling local policies and cultures of park use seem to play an important role for the potential positive effect.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- International study with comparable methods
- Associations between built environment(BE) and active transport(AT)
- Finding both linear and curvilinear relationships
- Adding to the discussion on generalizability across countries

Table 1

Descriptive statistics of transport-related walking and cycling

Study site	n	Any walking %	Any cycling %	Total day/week walking* M (SD)	Total day/week cycling* M (SD)
Total sample	11,674	72.5	14.8	3.2 (2.7)	0.5 (1.5)
AUS- Adelaide	2,443	76.6	11.6	3.2 (2.5)	0.4 (1.2)
BEL- Ghent	1,142	52.1	43.6	2.0 (2.4)	1.7 (2.4)
BRZ- Curitiba	693	77.3	7.5	3.5 (2.6)	0.3 (1.2)
COL- Bogota	958	90.3	9.3	4.8 (2.6)	0.3 (1.2)
CZ- Olomouc	264	83.2	19.3	4.6 (2.8)	0.6 (1.5)
DEN- Aarhus	599	79.5	61.6	3.3 (2.6)	2.4 (2.6)
MEX- Cuernavaca	611	90.3	1.3	4.5 (2.5)	0.0 (0.4)
NZ- Christchurch	481	55.9	17.5	2.0 (2.4)	0.5 (1.5)
NZ- North Shore	490	65.1	6.1	2.5 (2.5)	0.2 (0.8)
NZ- Waitakere	502	62.2	7.2	2.1 (2.2)	0.2 (1.0)
NZ- Wellington	493	85.2	8.1	4.1 (2.5)	0.2 (1.0)
UK- Stoke-on-Trent	815	65.5	3.9	3.0 (2.8)	0.1 (0.8)
US- Baltimore	902	68.1	6.5	2.9 (2.7)	0.2 (0.8)
US- Seattle	1,281	68.2	9.1	2.9 (2.6)	0.2 (1.0)

Notes.

* Including participants with 0 min/week or 0 day/week. M = mean; SD = standard deviation.

Only participants with complete data were included in the analyses.

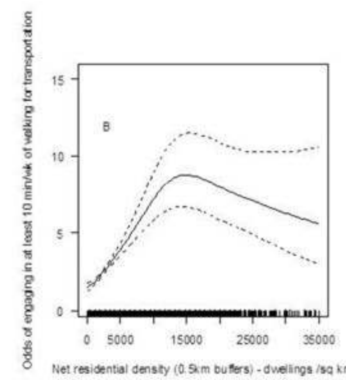
Table 2

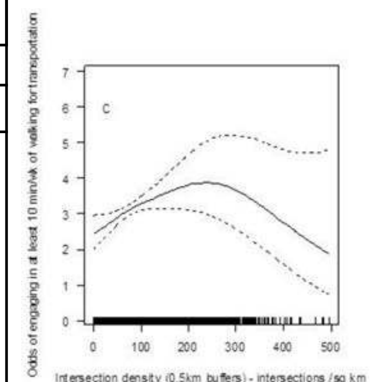
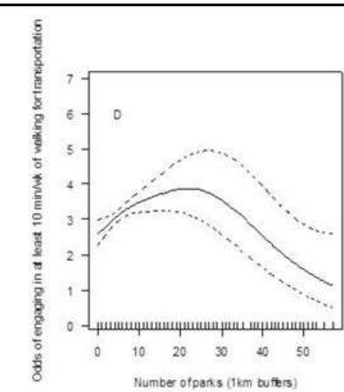
Descriptive statistics of objectively-assessed environmental attributes for 500 m buffer

Environmental attribute	ALL SITES	AUS-Adelaide	BEL-Ghent	BRA-Curitiba	COL-Bogota	CZE-Olomouc	DEN-Aarhus	MEX-Cuernavaca	NZ				UK-Stoke-on-Trent	USA	
									Site A	Site B	Site C	Site D		Site E	Site F
Net residential density (per km^2)															
Median (IQR)	2617 (4294)	1578 (922)	5196 (9327)	4819 (3256)	13086 (6979)	15326 (18173)	4646 (15728)	2328 (1833)	1534 (661)	1771 (451)	2478 (967)	2037 (4063)	4167 (1919)	2262 (2004)	1784 (3503)
Land use mix (3 uses)															
Median (IQR)	0.35 (0.49)	0.27 (0.48)	0.51 (0.53)	0.51 (0.33)	0.48 (0.33)	0.54 (0.29)	0.81 (0.44)	0.41 (0.47)	0.12 (0.24)	0.25 (0.46)	0.11 (0.48)	0.33 (0.62)	0.18 (0.38)	0.28 (0.48)	0.23 (0.48)
Intersection density (per km^2)															
Median (IQR)	77 (66)	75 (38)	74 (74)	80 (28)	195 (176)	74 (28)	106 (37)	165 (104)	36 (12)	29 (19)	33 (16)	41 (31)	118 (58)	77 (38)	59 (39)
No. parks contained or intersected by buffer															
Median (IQR)	2.0 (2.0)	3.0 (3.0)	1.0 (2.0)	1.0 (3.0)	7.0 (7.0)	1.0 (2.0)	1.0 (2.0)	0.0 (1.0)	1.0 (1.0)	4.0 (3.0)	3.0 (2.0)	1.0 (1.0)	1.0 (1.0)	1.0 (2.0)	1.0 (1.0)

Table 3

Associations of built environment attributes with any walking for transport (n=11,674)

Built environment variable (unit)	Buffer size	Model	Linear association		Interactions by study site	Curvilinear (MEV Model)
			OR (95% CI)	p		
Net residential density (1000 dwellings/km^2)	1km	SEV	2.33$^{\#}$ (1.07, 5.01)	0.030	Adelaide Ghent Aarhus Seattle Baltimore	
		MEV	1.90$^{\#}$ (0.99, 3.66)	0.055	Adelaide Ghent Aarhus Seattle Baltimore	
	500m	SEV	1.06$^{\#}$ (1.04, 1.07)	<0.001	NS.	
		MEV	**2.51$^{\#}$ (1.19, 5.34)**	**<0.001**	**NS.**	
Land use mix - 3 uses	1km	SEV	2.58 (2.01, 3.30)	<0.001	Ghent Wellington Seattle	NONE
		MEV	1.52 (1.17, 1.97)	0.001	Ghent Wellington Seattle	
	500m	SEV	2.22 (1.78, 2.76)	<0.001	Ghent Seattle	
		MEV	**1.48 (1.17, 1.86)**	**<0.001**	**NS.**	

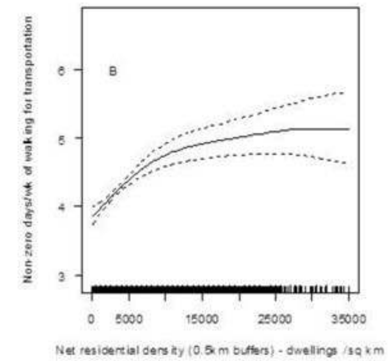
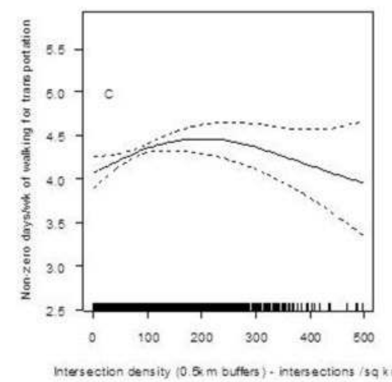
Built environment variable (unit)	Buffer size	Model	Linear association		Interactions by study site	Curvilinear (MEV Model)
			OR (95% CI)	p		
Intersection density (100 intersections/km^2)	1km	SEV	1.71$^{\#}$(1.42, 2.04)	<0.001	NS.	
		MEV	-	-	NS.	
	500m	SEV	1.43$^{\#}$(1.24, 1.64)	<0.001	NS.	
		MEV	**0.99$^{\#}$(0.79, 1.25)**	**0.963**	**NS.**	
No. parks contained or intersected by buffer (1 park/km^2)	1km	SEV	1.02 (1.01, 1.03)	0.005	NS.	
		MEV	**1.00$^{\#}$(0.97, 1.03)**	**0.805**	**NS.**	
	500m	SEV	1.03 (1.00, 1.06)	0.026	Ghent Aarhus Seattle	
		MEV	-	-	NS.	

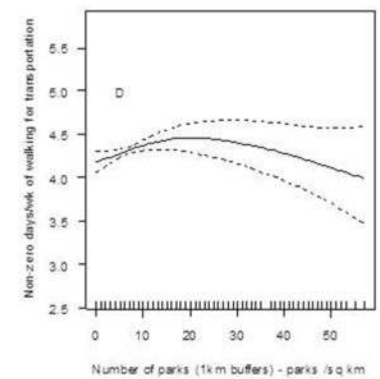
Notes. SEV = single-environment-variable model; MEV = multi-environment-variable model; OR = odds ratio; 95 % CI = 95% confidence intervals; ; - = excluded from the model as not a significant independent correlate of the outcome.

[#] significant curvilinear relationship (see corresponding Figure); All regression coefficients are adjusted for respondents' age, sex, marital status, educational attainment, employment status, administrative-unit socio-economic status, and city.

Table 4

Associations of built environment attributes with days of walking for transportation (n=8,462)

Built environment variable (unit)	Buffer size	Model	Days/week of walking exp(b) (95% CI)	Days/week of walking p	Interactions by study site	Curvilinear (MEV Model)
Net residential density (1000 dwellings/km^2)	1km	SEV	1.01[#] (1.01, 1.01)	<0.001	NS.	
		MEV	1.09[#] (1.00, 1.18)	0.045	NS.	
	500m	SEV	1.01[#] (1.01, 1.01)	<0.001	NS.	
		MEV	**1.10[#] (1.00, 1.20)**	**0.049**	NS.	
Land use mix - 3 uses	1km	SEV	1.10 (1.04, 1.17)	0.002	NS.	NONE
		MEV	-	-		
	500m	SEV	1.09 (1.03, 1.15)	0.001	NS.	
		MEV	-	-		
Intersection density (100 intersections/km^2)	1km	SEV	1.08 (1.04, 1.12)	<0.001	Adelaide Ghent Aarhus Wellington Seattle	
		MEV	-	-		
	500m	SEV	1.04[#] (1.02, 1.07)	0.002	NS.	
		MEV	**1.01[#] (0.96, 1.06)**	**0.746**	NS.	

Built environment variable (unit)	Buffer size	Model	Days/week of walking		Interactions by study site	Curvilinear (MEV Model)
			exp(b) (95% CI)	p		
No. parks contained or intersected by buffer (1 park/ km^2)	1km	SEV	1.00# (1.00, 1.01)	0.018	Ghent Aarhus North Shore Waitakere Seattle	
		MEV	**1.00# (1.00, 1.01)**	**0.956**	Ghent Aarhus North Shore Waitakere Seattle	
	500m	SEV	1.01 (1.00, 1.01)	0.018	NS.	
		MEV	-	-		

Notes. SEV = single-environment-variable model; MEV = multi-environment-variable model; exp(b) = antilogarithm of regression coefficient to be interpreted as the proportional increase in the outcome associated with a unit increase in the predictor; exp(95% CI) = antilogarithm of confidence intervals; - = excluded from the model as not a significant independent correlate of the outcome; All regression coefficients are adjusted for respondents' age, sex, marital status, educational attainment, employment status, administrative-unit socio-economic status, and city.

Table 5

Associations of built environment attributes with cycling for transportation

Built environment variable (unit of measurement)	Buffer size	Model	At least 10 min/week of cycling (ref cat: walking <10 min/week) (n=11,674)		Interactions	Non-zero days/week of cycling (n=1,728)		Interaction
			OR 95% CI	p	Study site	exp(b) (95% CI)	p	Study site
Net residential density (1000 dwellings/km^2)	1km	SEV	1.03 (1.01, 1.04)	<0.001	NS.	1.01 (1.00, 1.02)	0.004	NS.
		MEV	-	-		-	-	
	500m	SEV	1.01 (1.00, 1.02)	0.250	NS.	1.00 (1.00, 1.01)	0.002	NS.
		MEV	-	-		-	-	
Intersection density (100 intersections/km^2)	1km	SEV	1.40 (1.15, 1.69)	<0.001	NS.	1.07 (0.99, 1.17)	0.100	NS.
		MEV	1.35 (1.11, 1.64)	0.002	NS.	-	-	
	500m	SEV	1.29 (1.11, 1.50)	<0.001	NS.	1.06 (0.98, 1.13)	0.141	NS.
		MEV	1.26 (1.09, 1.47)	0.002	NS.	-	-	
Land use mix - 3 uses	1km	SEV	1.47 (1.08, 2.01)	0.015	NS.	1.26≠ (1.09, 1.45)	0.002	NS.
		MEV	1.29 (1.00, 1.67)	0.049	NS.	-	-	
	500m	SEV	1.39 (1.06, 1.81)	0.018	NS.	1.21≠ (1.06, 1.37)	0.004	NS.
		MEV	1.32 (1.01, 1.73)	0.042	NS.	-	-	
No. parks contained or intersected by buffer (1 park/km^2)	1km	SEV	0.99 (0.98, 1.01)	0.268		1.00 (0.99, 1.00)	0.504	NS.
		MEV	-	-		-	-	
	500m	SEV	0.99 (0.96, 1.02)	0.513		0.99 (0.98, 1.01)	0.491	Ghent Aarhus Seattle
		MEV	-	-		-	-	Ghent Aarhus Seatle

Notes. SEV = single-environment-variable model; MEV = multi-environment-variable model; OR = odds ratio; 95 % CI = 95% confidence intervals; exp(b) = antilogarithm of regression coefficient to be interpreted as the proportional increase in the outcome associated with a unit increase in the predictor; exp(95% CI) = antilogarithm of confidence intervals; - = excluded from the model as not a significant independent correlate of the outcome;

≠only significant built environment correlate after adjusting for other built environment correlates significant in the SEV models. All regression coefficients are adjusted for respondents' age, sex, marital status, educational attainment, employment status, administrative-unit socio-economic status, and city.