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Do physical activity and sedentary time mediate the association of the perceived environment with BMI? The IPEN Adult study

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COMPETING INTERESTS
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Abstract

The study's main aim was to examine whether adults' accelerometer-based physical activity and sedentary time mediated the associations of neighbourhood physical environmental perceptions with body mass index (BMI) and weight status across 10 high- and middle-income countries. Data from the IPEN Adult study, an observational multi-country study (n=5712) were used. Results showed that sedentary time was a non-significant or inconsistent mediator in all models. MVPA mediated the associations of street connectivity, land use mix-diversity, infrastructure/safety for walking and aesthetics with BMI in single models. In the multiple model, MVPA only fully mediated the relation between land use mix-diversity and BMI. This finding was replicated in the models with weight status as outcome. MVPA partially mediated associations of composite environmental variables with weight status. So, although MVPA mediated some associations, future comprehensive studies are needed to determine other mechanisms that could explain the relation between the physical environment and weight outcomes. Food intake, food accessibility and the home environment may be important variables to consider. Based on the consistency of results across study sites, global advocacy for policies supporting more walkable neighbourhoods should seek to optimize land-use-mix when designing and re-designing cities or towns.

Keywords

Exercise; Adults; Physical Activity; Community Health

INTRODUCTION

Overweight and obesity are major global health problems (NCD Risk Factor Collaboration, 2016). From 1975 to 2014, the age-standardised global prevalence of obesity in adults increased from 3.2% to 10.8% in men, and from 6.4% to 14.9% in women (NCD Risk Factor Collaboration, 2016). Overweight and obesity are risk factors for chronic non-communicable diseases like type 2 diabetes, cardiovascular diseases, and specific types of cancer (breast cancer, ovarian cancer and prostate cancer), putting substantial pressure on national economies through increased medical costs and indirect costs (e.g. absenteeism at work) (Chu et al, 2018). It should be noted that the risk of non-communicable diseases is higher for obese (BMI ≥30 kg/m^2) than overweight individuals (BMI ≥25 kg/m^2) (Nejat et al, 2010).

Longitudinal studies indicate that insufficient physical activity (PA) is consistently associated with weight gain and development of overweight and obesity (Reiner et al, 2013). Moreover, a growing number of epidemiological studies have indicated that high levels of objectively-assessed and self-reported sedentary time (ST) are associated with higher levels of adiposity, independent of PA (Cleland et al, 2018; Gibbs et al, 2017; Golubic et al, 2015). However, the findings on ST and overweight/obesity are not as consistent as those for PA (Campbell et al, 2018; Ekelund et al, 2017).

To develop effective behavioural interventions for overweight/obesity prevention, it is crucial to identify the main determinants of the target behaviours. Socio-ecological models of health behaviours (Sallis et al, 2015) state that in addition to individual and social-level factors, characteristics of the physical environment can be important determinants of PA and ST. One setting in which physical environmental characteristics can be examined is the residential neighbourhood (i.e., area within ~1 km radius from a person's home). A focus on these characteristics may be very useful for population-based intervention strategies, as environmental changes can affect the behaviour of large groups of residents on a relatively permanent basis (Heath et al, 2006).

Previous studies, both in single high- and middle-income (Jauregui et al, 2016; Jansen et al, 2018) and multiple countries (Sallis et al, 2016) found consistent associations between specific physical environmental attributes and moderate-to-vigorous PA (MVPA) in adults. For instance, Sallis and colleagues (2016) found that objectively-assessed neighbourhood residential density, public transport density, intersection density and number of parks were positively and linearly related to accelerometer-assessed MVPA in adults in 10 countries worldwide. Regarding the association between physical environmental attributes and overall ST, results are inconclusive. Owen et al (2018) reported that higher perceived street connectivity was related to less accelerometer-assessed sedentary time (ST), but higher residential density, better pedestrian infrastructure and safety and fewer physical barriers in the neighbourhood were unexpectedly associated with more ST in 10 countries. Inconsistent associations of neighbourhood physical environmental attributes with self-reported and objectively-measured ST have also been reported in a systematic review (O'Donoghue et al, 2016).

The direct link of physical environmental characteristics with overweight and obesity also has been examined. Current evidence suggests that the strength of associations with weight outcomes depends on which environmental characteristics are examined. Residential density and land use mix have been consistently and negatively related to obesity (Lakerveld & Mackenbach, 2017), while evidence for other characteristics, such as green spaces, traffic safety and street connectivity is inconclusive (Mackenbach et al, 2014).

In summary, a large body of research examined associations of the neighbourhood physical environment with PA, ST, and weight outcomes in adults. Except for the well-established association with MVPA, results are inconsistent. Examining the pathways between the physical environment, PA, ST, and weight outcomes may be helpful to clarify previous findings. A few studies already examined whether PA and/or ST mediated the relationships between the physical environment and weight outcomes (Malambo et al, 2017; Van Dyck et al, 2010; Poortinga, 2006). While Poortinga (2006) and Malambo et al (2017) found that self-reported PA was not a mediator of the associations between perceived environmental characteristics and adults' weight outcomes, results of a Belgian study showed that accelerometer-assessed MVPA mediated the association between neighbourhood walkability and BMI. Accelerometer-assessed ST was not a significant mediator in that study (Van Dyck et al, 2010). Comparable results were reported in a study of New Zealand adults (Oliver et al, 2015): accelerometer-based MVPA mediated the association of street connectivity and destination accessibility with body size, while accelerometer-assessed ST was not a significant mediator.

These mixed results call for further investigation. To our knowledge, all currently available studies examined these mediating effects within single countries or single cities. The diversity in results may be partly explained by the limited variability in environmental characteristics, health behaviours, and weight outcomes that is inherent when conducting single country studies. The main aim of our study was to examine accelerometer-based estimates of adults' PA and ST as mediators of associations between neighbourhood physical environmental perceptions and BMI across 12 cities in 10 high- and middle-income countries. Additionally, we examined whether these mediating effects and associations varied by study site (city). Examining potential moderating effects of study sites may provide insights into the generalizability of mediating effects and the potential of international strategies for the creation of non-obesogenic neighbourhood physical environments.

MATERIALS AND METHODS

Study design

We used data from the International Physical Activity and the Environment Network (IPEN) Adult study (http://www.ipenproject.org/). IPEN Adult was an observational epidemiologic multi-country study that used comparable protocols and measures across countries (Kerr et al, 2013). IPEN was designed to examine associations between the physical environment and PA, ST, and overweight/obesity across 17 sites from 12 countries: Australia (Adelaide), Belgium (Ghent), Brazil (Curitiba), Colombia (Bogota), Czech Republic (Olomouc, Hradec Kralove), Denmark (Aarhus), China (Hong Kong), Mexico (Cuernavaca), New Zealand (North Shore, Waitakere, Wellington, Christchurch), Spain (Pamplona), United Kingdom (Stoke-on-Trent), and the USA (Seattle, Baltimore). Data collection dates ranged from 2002 to 2011. For the present analyses, 10 countries (12 sites) with objective accelerometer-based (Actigraph; Pensacola, FL) PA data were included. Adelaide, Australia, was excluded because no accelerometer data were collected. The four sites in New Zealand were excluded because Actical (Philips Respironics, Bend, OR) devices were used instead of Actigraph, so ST data were not comparable.

Participants were recruited from neighbourhoods stratified into four quadrants based on walkability and socio-economic status (SES). All countries but Spain used an objectively defined walkability index based on Geographic Information Systems (GIS) data and census-level SES indicators to stratify neighbourhoods into the quadrants (Kerr et al, 2013). Spain used 'construction date' as a parameter for neighbourhood selection, which has been associated with walkability (Berrigan & Troiano, 2002). Ethical approval was obtained from each local institutional review board, and participants' informed consent was obtained.

Recruitment and participants

Residents recruited from the selected neighbourhoods completed surveys on their PA and neighbourhood environmental perceptions, and wore an accelerometer to objectively assess PA and ST (subsample in some countries). Details about participant sampling and recruitment strategies have been published elsewhere (Kerr et al, 2013). While recruitment methods varied substantially across countries, all used systematic strategies to reduce bias and to recruit approximately equal numbers of participants sampled across the four study design quadrants representing high/low walkability by high/low SES. Recruitment age ranged from 15 to 84 years, but only adult participants aged 18–66 years were included in analyses.

Data from 12 sites in 10 countries (5712 participants) were analysed. Only participants with 4 or more days of valid accelerometer data were included in the current analyses. While a weekend day was not specifically required, it is likely that most participants had at least one weekend day, as 84.8% of the analysis sample had 6 or more valid wearing days. The socio-demographics of the overall and site-specific samples can be found in Table 1.

Measures

BMI and weight status—BMI (kg/m^2) was computed using self-reported weight and height in seven countries and objective measures of the same in Brazil, Mexico and the UK. Self-reported and objectively-assessed BMI are highly correlated, and BMI is used as a proxy measure for adiposity in large-scale studies (McAdams et al, 2007). To obtain 'weight status', participants were categorized into participants with normal weight and with overweight/obesity (BMI ≥ 25 kg/m^2; https://www.who.int/news-room/fact-sheets/detail/obesity-and-overweight, Access verified on March 31, 2020).

Perceived attributes of the neighbourhood physical environment—The validated Neighbourhood Environment Walkability Scale (NEWS) or its abbreviated version (NEWS-A) was used to assess perceived neighbourhood attributes (Cerin et al, 2006; Saelens et al, 2003). Because IPEN countries used country-adapted versions of the NEWS, extensive harmonization work was undertaken to allow data pooling (Cerin et al, 2013). The following 10 NEWS subscales were used for the IPEN multi-country pooled analyses: residential density; land use mix-access; land use mix-diversity; street connectivity; infrastructure and safety for walking; aesthetics; safety from traffic; safety from crime; streets having few cul-de-sacs; and no major physical barriers to walking. Scoring details are described elsewhere (Cain, 2012).

Accelerometer-based estimates of moderate-to-vigorous physical activity and sedentary time—Mean minutes per day of MVPA and of ST were assessed objectively using ActiGraph accelerometers (Pensacola, FL, USA). Different models of the ActiGraph accelerometer were used in this study, including the 7164/71256 models, GT1M, ActiTrainer and GT3X models. Accelerometers are widely used in research to assess free-living PA and ST in adults and their reliability and validity have been documented extensively (Freedson & Miller, 2000). Participants were asked to wear the accelerometer above the right hip for seven consecutive days during waking hours and to remove it only for water-based activities (e.g., swimming, showering). Accelerometer data were collected in (or aggregated to) one-minute epochs. Data were screened and processed using MeterPlus version 4.3. by trained researchers at the IPEN Coordinating Center. Non-wear time was defined as ≥60 minutes of consecutive zero counts. Only data of participants with at least 10 valid wearing hours on at least four days were included in the analyses. Counts per minute were converted into minutes of ST (≤100 counts per minute) and minutes of MVPA (≥1952 counts per minute) (Freedson et al, 2011; Mattheuws et al, 2008). Further details about the accelerometer data collection and processing can be retrieved from the IPEN accelerometer protocol (Cain, 2012).

Socio-demographic characteristics—Age, gender, education ('less than high school graduate', 'high school graduate' and 'college degree or higher'), employment status ('employed' and 'not employed') and marital status ('married/living with partner' and 'not living with partner') were self-reported.

Data analytic plan

Descriptive statistics were computed for the whole sample and by city. Generalized additive mixed models (GAMMs) (Wood, 2006), accounting for administrative unit-level clustering arising from the two-stage sampling strategy used in the study, were employed to estimate MVPA and ST as mediators of the associations of perceived neighbourhood attributes with BMI and weight status. GAMMs were used because they can accommodate outcomes with various distributional assumptions and estimate curvilinear dose-response relationships of unknown form using smooth terms. GAMMs with Gamma variance and logarithmic link functions were used to model MVPA and BMI (as a continuous measure) due to the positively skewed distribution of these outcome variables. Binomial variance and logit link functions were used to model weight status as a dichotomous variable (normal vs. overweight/obese), while ST and perceptions of the neighbourhood environment were modelled using GAMMs with Gaussian variance and identity link functions.

Analyses were conducted in four steps. We first estimated the covariate-adjusted associations of single and multiple perceived neighbourhood attributes with BMI and weight status (outcomes). The multiple environmental variable models included only those perceived neighbourhood attributes that were significantly related to the outcomes. It was possible to enter multiple perceived neighbourhood attributes in the models because their inter-correlations were not high ($r<0.40$; see Supplementary Table 1). We also estimated the relationships of composite measures of perceived neighbourhood attributes with BMI and weight status. Composite measures represented the sum of the z-scores of all attributes that were significant predictors in the single or multiple environmental variable models of BMI and weights status. Curvilinear relationships were estimated using thin plate splines (Wood, 2006). Smooth terms failing to provide sufficient evidence of a curvilinear relation (based on the Akaike Information Criterion [AIC] of the model assuming curvilinearity being < 10 units smaller than the AIC value of the model assuming linearity) were replaced by simpler linear terms (Burnham, 2002). In step 2 of the analyses, appropriate two-way interaction terms were added to the above GAMMs to estimate the moderating effects of city on the above associations. Moderation effects were deemed significant if the inclusion of the interaction term in the model yielded a >10-unit smaller AIC than the main effect model.

Third, we examined whether MVPA and/or ST mediated statistically significant associations between single, multiple and composite measures of perceived neighbourhood attributes and BMI and/or weight status. This was done by first regressing MVPA and ST (potential mediators) onto the perceived neighbourhood attribute(s) measures significantly associated with the outcome(s) (BMI or weight status) (step 3 of the analyses). Also, perceived neighbourhood attribute measures by city interaction terms were added to a model if significant moderating effects of city were found in step 2 of the analyses. In step 4 of the analyses, we regressed the outcomes (BMI and/or weight status) onto perceived neighbourhood attribute(s) measures, MVPA, ST and, when appropriate, neighbourhood attribute measure by city interaction terms. We used the joint-significance test to determine mediation (MacKinnon & Luecken, 2008), whereby mediation is confirmed if a perceived neighbourhood attribute measure is significantly related to the mediator (MVPA and/or ST) and the mediator (MVPA and/or ST) is significantly related to the outcome (BMI and/or weight status) after adjustment for the perceived neighbourhood attribute. As only 4.5% cases had missing data, data analyses were performed on complete cases (Cerin et al, 2014). All analyses were conducted in R (R Development Core Team, 2015). GAMMs were estimated using the package ‘mgcv’ (Wood, 2006) in R.

RESULTS

In total, 5712 adults (18 – 66 years) provided valid data and were included in the analyses. Mean age was 43 years (SD 12.4) and 46.7% of participants were male. Overall 49.8% of the participants had a BMI in the normal range, 33.1% were overweight, and 16.1% obese. The prevalence of overweight and obesity across sites ranged from 22% (Hong Kong, China) to 72% (Cuernavaca, Mexico) (Table 1). Average accelerometer-based MVPA was 36.3 min/day, ranging from 29.2 (SD 22.0) min/day in Baltimore, USA, to 51.0 (SD 29.5) min/day in Pamplona, Spain. Mean ST was 513 min/day (approximately 8.5 hours/day) and was lowest in Bogota, Colombia (463 min/day, SD 92), and highest in Aarhus, Denmark (572 min/day, SD 91).

Associations of perceived neighbourhood attributes with BMI and weight status

Single environmental variable models indicated significant negative linear associations between BMI and perceived street connectivity, land use mix-diversity, aesthetics, infrastructure/safety for walking, traffic safety and safety from crime (Table 2). For example, a unit increase in perceived traffic safety was associated with a 1.2% lower BMI unit ($p < 0.001$). A composite measure of perceived environmental attributes, defined as the sum of the z-scores of all attributes significantly related to BMI in the single-environmental-variable models, was also linearly negatively related to BMI (Table 2). Multiple-environmental variable models showed that only perceived traffic safety, safety from crime and land use mix-diversity independently contributed to the explanation of BMI (underlined values in Table 2). A composite measure of these perceived neighbourhood attributes displayed the strongest association with BMI. Perceived residential density and land use mix-diversity were negatively associated with the odds of being overweight/obese in the single environmental variable models (Table 2). A composite measure encompassing these two perceived environmental attributes showed a strong negative association with overweight/obesity. Only perceived residential density remained a significant correlate when adjusting for the other neighbourhood attributes. Hence, no multiple environmental variable models were reported for weight status (Table 2). City was not a significant moderator of the above associations (Supplementary Table 2).

Mediation models of BMI

Single environmental variable mediation models indicated that MVPA was a significant (full or partial) mediator of the associations of perceived street connectivity, land use mix-diversity, infrastructure/safety for walking and aesthetics, but not of traffic safety and safety from crime, with BMI (Table 3). This is because only the former set of perceived neighbourhood attributes were positively related to MVPA (Table 3, column A) and MVPA was curvilinearly related to BMI after adjustment for the neighbourhood attributes (Table 3, column B, Supplementary Figures). A stronger approximately linear relationship was observed between MVPA and BMI for MVPA values ranging from 0 to ~40 min/day. The estimated effects of MVPA on BMI levelled off at higher levels of activity and were nil at >150 min/day of MVPA (Supplementary Figures). ST did not mediate any of the associations between neighbourhood attributes with BMI because it either was unrelated to the specific attributes (e.g. land use mix-diversity; see Table 3, column A) or was unrelated to BMI after adjustment for the relevant neighbourhood attributes and MVPA (e.g. aesthetics; see Table 3, column B). Multiple-environmental variable mediation models of BMI revealed that MVPA mediated only the relationship between land use mix-diversity and BMI (Table 3, underlined values; Figure 1). MVPA also mediated the association between composite measures of perceived environmental attributes and BMI (Table 3).

Mediation models of weight status

As only perceived residential density and land use mix-diversity were significantly negatively related to the odds of being overweight / obese in single environmental variable models (Table 2), we estimated single environmental variable mediation models for these two neighbourhood attributes (Table 4). ST acted as a suppressor (i.e. inconsistent mediator) of the negative associations between perceived residential density and the odds of being overweight or obese. This is because residential density was positively related to ST (Table 4, column A) and ST was positively related to the odds of being overweight or obese (Table 4, column B). Also, after adjusting for ST, the negative association between perceived residential density and the odds of being overweight or obese strengthened (see Table 2 and Table 4, column C). MVPA mediated the relationship of land use mix–diversity and the composite measure of perceived environmental attributes with weight status because these exposure measures were positively related to MVPA, and MVPA was negatively curvilinearly related to the odds of being overweight/obese (Figures 2 and S7).

DISCUSSION

This was the first multi-country study examining the mediating effects of objectively-assessed MVPA and ST in the relation between the neighbourhood physical environment and BMI/weight outcomes in adults. Analyses showed rather limited mediating effects of MVPA and ST. ST was a non-significant or inconsistent mediator in all models. In the single environmental variable models MVPA mediated the associations of street connectivity, land use mix-diversity, infrastructure/safety for walking and aesthetics with BMI. However, in the multiple environmental model that controlled for the other environmental attributes, MVPA only remained a mediator of the relation between land use mix-diversity and BMI. MVPA partially mediated the relation between the composite indices (single and multiple environmental variable indices) and BMI, but these findings might be guided by the full mediation effect of MVPA on the association between land use mix-diversity and BMI. These findings were replicated in the models with weight status as the outcome. So, the availability of different land uses (e.g., supermarkets, green spaces) nearby was related to more MVPA and indirectly to a lower BMI and lower odds of being overweight/obese. The particular importance of land use mix-diversity could be because this variable signifies the proximity of multiple commonly-used destinations within walking distance, such as shops, services, and food outlets. Overall, our findings are in line with those of Oliver et al (2015) and Van Dyck et al (2010) showing that objectively-assessed PA, but not ST, mediated the relationship between walkability attributes and BMI. [Note that the Belgian data reported in Van Dyck et al (2010) were included in present 10-country analyses.] Similarly, mediating effects of total self-reported PA but not of self-reported ST were reported in a sample of Nigerian adults (Oyeyemi et al, 2013). Also, Brown and colleagues (2013) found mediating effects of accelerometer-assessed MVPA on the associations between walkability and BMI in US adults. Nonetheless, our results add specificity to previous findings, since MVPA partially mediated associations of overall walkability with weight outcomes, but this finding was mainly due to a distinct walkability aspect, namely land-use-mix diversity, whose association with weight outcomes was fully mediated by MVPA. This could have implications for policy recommendations and urban planning choices. If confirmed in future studies, it may be primarily important for health to optimize land-use-mix that provides diverse destinations within walking distance of people's homes when advocating for more walkable neighbourhoods in general.

Results showed that none of the associations or mediating effects were moderated by study site. This implies that the results presented in this paper have international applicability, as 10 culturally and geographically diverse countries worldwide were included. The consistency of the findings across countries suggests that strategies to optimize/increase positive perceptions of physical environments (e.g. land use mix-diversity, traffic and crime safety) have potential to positively affect BMI on a global scale.

Our findings showed that two thirds (4/6) of the associations between the neighbourhood physical environment and BMI were mediated by MVPA in the single variable models. Nonetheless, mediation effects were limited in the multiple variable model. This may be due to the shared variance between aesthetics and safety from crime, and among land use mix-diversity, street connectivity, and infrastructure/safety for walking. Each of these variables probably have small independent effects on BMI. This assumption was confirmed in analyses including the composite indices. These analyses showed the direct associations between the composite indices and BMI/weight status were stronger than the associations identified in the single and multiple variable models. In addition, MVPA partially mediated the relation between the composite environmental indices and the weight outcomes.

Furthermore, because mediation by MVPA was partial, other variables (e.g. food intake) should be considered as well. Food intake is inextricably linked to BMI and weight status (Morenga et al, 2013), and the presence of healthy food options in the neighbourhood has been related to more fruit and vegetable intake (Alber et al, 2018), a result confirmed in a recent review (Bivoltsis et al, 2018). Potentially, other physical environmental variables (e.g., residential density) may also be related to food intake and indirectly to weight outcomes. To gain more insight into this, future studies should include both PA and food intake measures when examining mediators between the neighbourhood environment and weight outcomes.

The fact that no or suppressive mediating effects of ST were identified confirms the inconsistent associations previously found between the physical environment and ST (Owen et al, 2018; O'Donoghue et al, 2016), and between ST and weight outcomes (Gibbs et al, 2017; Ekelund et al, 2017). Perhaps the physical environmental attributes that are consistently linked with MVPA are not particularly relevant for overall ST. Other neighbourhood (e.g. presence of benches) and home environmental factors (e.g. number of televisions, televisions in the bedroom, presence of stairs), as well as policies (e.g. parking and traffic policies) might be more relevant to include in future studies examining mediating effects of ST. Furthermore, domain-specific measures of ST (e.g. passive transport, watching television) might be more strongly related to neighbourhood environmental correlates, and hence, more relevant to examine (Chastin et al, 2013).

Study strengths included the large sample size, use of comparable data collection protocols in 10 countries, use of objective methods (accelerometers) to measure MVPA and ST, and application of complex statistical models to assess mediation and moderation by city. A first limitation was the cross-sectional study design, making it impossible to draw conclusions regarding causality. Second, participants were recruited from specific neighbourhoods selected on walkability and income levels, so results may not be generalizable to entire adult populations. Third, both self-reported and objective measures were used across countries to determine BMI and weight status, which could have biased the results. Fourth, accelerometers are not optimal for assessing ST because they cannot distinguish between sitting and standing (Atkin et al, 2012) and cannot capture context-specific behaviours such as screen time and car use. Incorporating inclinometers and validated domain-specific questionnaires in future studies is encouraged, but this can be challenging from a practical viewpoint. Fifth, response rates and Actigraph models varied across study sites, possibly implying sampling biases and measurement errors. Finally, only perceived environmental attributes were used in this study. Future studies may benefit from including objective measures of the built environment, or a combination of objective and perceived measures.

CONCLUSION

In conclusion, this study revealed that objectively-measured MVPA mediated two thirds of the associations between physical environmental variables and BMI in the single models. In the multiple variable models, MVPA mediated the association of land use mix-diversity with both BMI and being overweight/obese across 10 countries worldwide. Furthermore, MVPA mediated the associations of composite environmental indices with BMI and weight status. These composite indices included those environmental perceptions that were directly associated with the weight outcomes in the single and multiple environmental variable models. It was notable that all results generalized across diverse international cultures and geographies. ST was not identified as a mediator. If confirmed in future longitudinal studies, especially increasing land use mix-diversity, crime safety and traffic safety in cities worldwide may have positive effects on weight outcomes. Specifically for land use mix-diversity, part of this association is explained by increased MVPA, but other mediating factors remain to be determined.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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ETHICAL APPROVAL

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REFERENCES

Alber JM, Green SH, Glanz K. Perceived and observed food environments, eating behaviors and BMI. Am J Prev Med 2018; 54: 423–429. [PubMed: 29338954]

Atkin AJ, Gorely T, Clemes SA, et al. Methods of measurement in epidemiology: sedentary behaviour. Int J Epidemiol 2012; 41: 1460–1471. [PubMed: 23045206]

Berrigan D, Troiano RP. The association between urban form and physical activity in U.S. adults. Am J Prev Med 2002; 23: 74–79. [PubMed: 12133740]

Bivoltsis A, Cervigni E, Trapp G, Knuiman M, Hooper P, Ambrosini GL. Food environments and dietary intakes among adults: does the type of spatial exposure measurement matter? A systematic review. Int J Health Geogr 2018; 17: 19. [PubMed: 29885662]

Brown BB, Smith KR, Hanson H, Fan JX, Kowaleski-Jones L, Zick CD. Neighborhood design for walking and biking, physical activity and body mass index. Am J Prev Med 2013; 44: 231–238. [PubMed: 23415119]

Burnham KP, Anderson DR. Model Selection and Multimodel Inference: a Practical Information-theoretic Approach. 2nd ed. New York: Springer; 2002.

Cain KL. Accelerometer Scoring Protocol for the IPEN-Adult Study. University California San Diego, CA [Web page]. http://www.ipenproject.org/documents/methods_docs/

Accelerometer_Data_Collection_and_Scoring_Manual_Updated_June2012.pdf Accessed December 5, 2019.

Campbell SDI, Brosnan BJ, Chu AKY, et al. Sedentary behaviour and body weight composition in adults: a systematic review and meta-analysis of prospective studies. Sports Med 2018; 48: 585–595. [PubMed: 29189928]

Cerin E, Cain K, Conway TL, et al. Neighborhood environments and objectively measured physical activity in 11 countries. Med Sci Sports Exerc 2014; 46: 2253–2264. [PubMed: 24781892]

Cerin E, Conway TL, Cain KL, et al. Sharing good NEWS across the world: developing comparable scores across 12 countries for the Neighborhood Environment Walkability Scale (NEWS). BMC Public Health 2013; 13:309. [PubMed: 23566032]

Cerin E, Saelens BE, Sallis JF, Frank LD. Neighborhood environment walkability scale: validity and development of a short form. Med Sci Sports Exerc 2006; 38: 1682–91. [PubMed: 16960531]

Chastin SFM, Schwarz U, Skelton DA. Development of a consensus taxonomy of sedentary behaviors (SIT): Report of Delphi round 1. PLoS ONE 2013; 8: e82313. [PubMed: 24312653]

Chu DT, Minh Nguyet NT, Dinh TC, et al. An update on physical health and economic consequences of overweight and obesity. Diabetes Metab Syndr 2018; 12: 1095–1100. [PubMed: 29799416]

Cleland VJ, Patterson K, Breslin M, Schmidt MD, Dwyer T, Venn AJ. Longitudinal associations between TV viewing and BMI not explained by the 'mindless eating' or 'physical activity displacement' hypotheses among adults. BMC Public Health 2018; 18: 797 [PubMed: 29940922]

Ekelund U, Kolle E, Steene-Johannessen J, et al. Objectively measured sedentary time and physical activity and associations with body weight gain: does body weight determine a decline in moderate and vigorous physical activity? Int J Obes 2017; 41: 1769–1774.

Freedson PS, Miller K. Objective monitoring of physical activity using motion sensors and heart rate. Res Q Exerc Sport 2000; 71: S21–9. [PubMed: 10925821]

Freedson PS, Lyden K, Kozey-Keadle S, Staudenmayer J. Evaluation of artificial neural network algorithms for predicting METs and activity type from accelerometer data: Validation on an independent sample. J Appl Physiol 2011; 111: 1804–1812. [PubMed: 21885802]

Gibbs BB, Gabriel KP, Carnethon MR, et al. Sedentary time, physical activity, and adiposity: cross-sectional and longitudinal associations in CARDIA. Am J Prev Med 2017; 53: 764–771. [PubMed: 29032856]

Golubic R, Wijndaele K, Sharp SJ, et al. Physical activity, sedentary time and gain in overall and central body fat: 7-year follow-up of the ProActive trial cohort. Int J Obes 2015; 39: 142–148.

Heath G, Brownson R, Kruger J, et al. The effectiveness of urban design and land use and transport policies and practices to increase physical activity: a systematic review. J Phys Act Health. 2006; 1: S55–S71.

Jansen M, Kamphuis CBM, Pierik FH, Ettema DF, Dijst MJ. Neighborhood-based PA and its environmental correlates: a GIS- and GPS based cross-sectional study in the Netherlands. BMC Public Health 2018; 18: 233. [PubMed: 29426309]

Jauregui A, Pratt M, Lamadrid-Figueroa H, Hernandez B, Rivera JA, Salvo D. Perceived neighbourhood environment and physical activity: the International Physical Activity and the Environment Network adult study in Mexico. Am J Prev Med 2016; 51: 271–279. [PubMed: 27180029]

Kerr J, Sallis JF, Owen N, et al. Advancing science and policy through a coordinated international study of physical activity and built environments: IPEN Adult methods. J Phys Act Health 2013; 10: 581–601. [PubMed: 22975776]

Lakerveld J, Mackenbach J. The upstream determinants of adult obesity. Obes Facts 2017; 10: 216–222. [PubMed: 28564658]

Mackenbach JD, Rutter H, Compernolle S, et al. Obesogenic environments: a systematic review of the association between the physical environment and adult weight status: the SPOTLIGHT project. BMC Public Health 2014; 14:233. [PubMed: 24602291]

MacKinnon DP, Luecken LJ. How and for whom? Mediation and moderation in health psychology. Health Psychol 2008; 27: S99–S100. [PubMed: 18377161]

Malambo P, Kengne AP, Lambert EV, De Villiers A, Puoane T. Does physical activity mediate the association between perceived neighborhood aesthetics and overweight/obesity among South

African adults living in selected urban and rural communities? J Phys Act Health 2017; 14: 925–932. [PubMed: 28682650]

Matthews CE, Chen KY, Freedson PS, et al. Amount of time spent in sedentary behaviors in the United States, 2003–2004. Am J Epidemiol 2008; 167: 875–881. [PubMed: 18303006]

McAdams MA, Van Dam RM, Hu FB. Comparison of self-reported and measured BMI as correlates of disease markers in US adults. Obesity 2007; 15:188–96. [PubMed: 17228047]

Morenga LT, Mallard S, Mann J. Dietary sugars and body weight: review and meta-analyses of randomized controlled trials and cohort studies. BMJ 2013; 346: e7492.

NCD Risk Factor Collaboration (NCD-RisC). Trends in adult body-mass index in 200 countries from 1975 to 2014: a pooled analysis of 1698 population-based measurement studies with 19.2 million participants. Lancet 2016; 387: 1377–1396. [PubMed: 27115820]

Nejat EJ, Polotsky AJ, Pal L. Predictors of chronic disease at midlife and beyond – the health risks of obesity. Maturitas 2010; 64: 106–111.

O'Donoghue G, Perchoux C, Mensah K, et al. A systematic review of correlates of sedentary behaviour in adults aged 18–65 years: a socio-ecological approach. BMC Public Health 2016; 16: 163. [PubMed: 26887323]

Oliver M, Witten K, Blakely T, et al. Neighbourhood built environment associations with body size in adults: mediating effects of activity and sedentariness in a cross-sectional study of New Zealand adults. BMC Public Health 2015; 15: 956. [PubMed: 26399257]

Owen N, Sugiyama T, Koohsari MJ, et al. Associations of neighborhood environmental attributes with adults' objectively-assessed sedentary time: IPEN adult multi-country study. Prev Med 2018; 115: 126–133. [PubMed: 30145352]

Oyeyemi AL, Deforche B, Sallis JF, De Bourdeaudhuij I, Van Dyck D. Behavioral mediators of the association between neighborhood environment and weight status in Nigerian adults. Am J Health Promot 2013; 28: 23–31. [PubMed: 23458369]

Poortinga W Perceptions of the environment, physical activity and obesity. Soc Sci Med 2006; 63: 2835–2846. [PubMed: 16952415]

Reiner M, Niermann C, Jekauc D, Woll A. Long-term health benefits of physical activity – a systematic review of longitudinal studies. BMC Public Health 2013; 13: 813. [PubMed: 24010994]

Saelens BE, Sallis JF, Black JB, Chen D. Neigborhood-based differences in physical activity: an environment scale evaluation. Am J Public Health 2003; 93: 1552–8. [PubMed: 12948979]

Sallis JF, Cerin E, Conway TL, et al. Physical activity in relation to urban environments in 14 cities worldwide: a cross-sectional study. Lancet 2016; 387: 2207–2217. [PubMed: 27045735]

Sallis JF, Owen N. Ecological models of health behavior In: Glanz K, Rimer BK, Viswanath K, eds. Health behavior: Theory, research and practice. San Francisco, CA: Jossey-Bass; 2015 pp. 43–64.

Van Dyck D, Cerin E, Cardon G, Deforche B, Sallis JF, Owen N, Bourdeaudhuij I. De Physical activity as a mediator of the associations between neighborhood walkability and adiposity in Belgian adults Health Place, 16 (2010), pp. 952–960 [PubMed: 20542461]

Wood SN. Generalized Additive Models: an Introduction with R. Boca Raton: Chapman and Hall; 2006

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Study highlights

- MVPA mediated the relation between land use mix-diversity and BMI/weight status.
- Sedentary time was not a significant mediator in any of the models.
- All findings were similar in the 10 countries included in the study.
- Data from the IPEN study, a large-scale observational multi-country study were used.

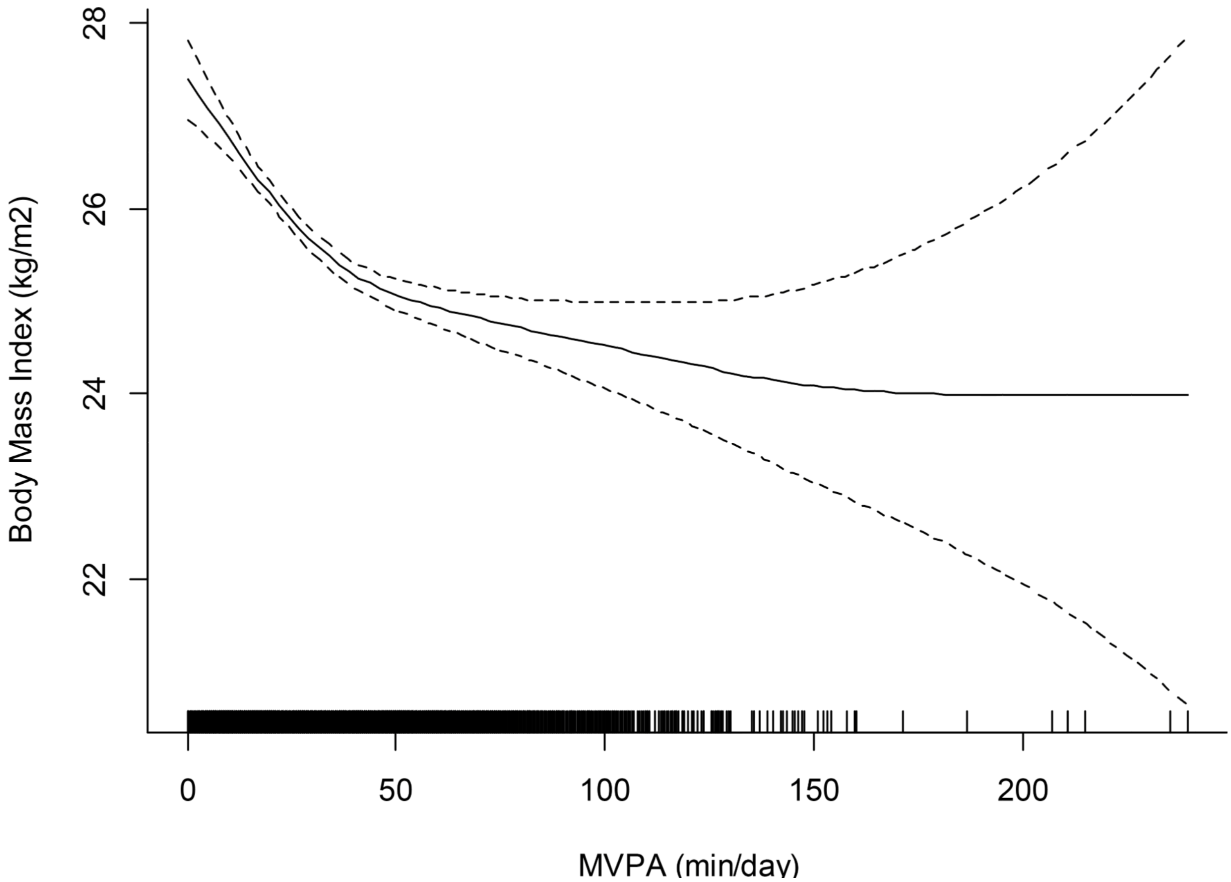

Figure 1:

Relationship between accelerometer-assessed moderate-to-vigorous physical activity (MVPA) and BMI adjusted for perceived land use mix-diversity, traffic safety and safety from crime (dashed lines represent 95% confidence intervals)

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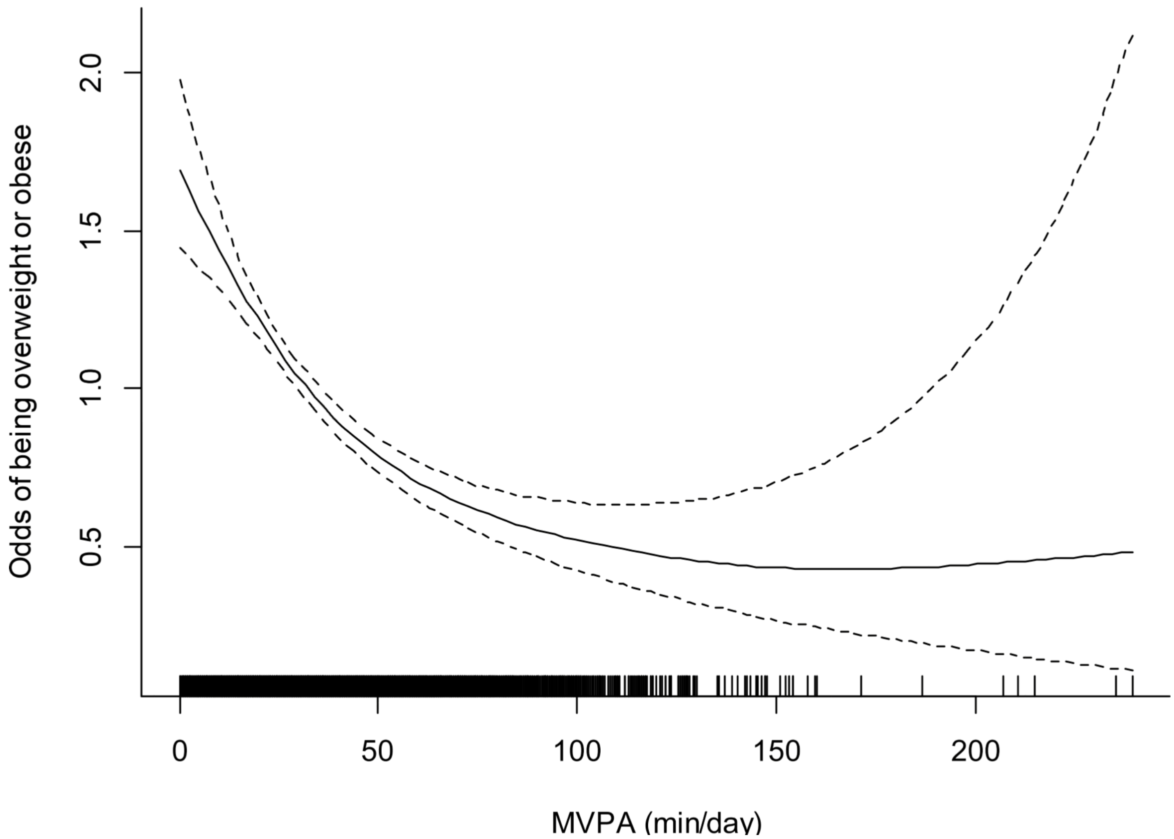

Figure 2:

Relationship between accelerometer-assessed moderate-to-vigorous physical activity (MVPA) and the odds of being overweight / obese adjusted for perceived land use mix-diversity (dashed lines represent 95% confidence intervals)

Table 1.

Descriptive statistics of sample characteristics by city and in the total sample

	Ghent, Belgium	Curitiba, Brazil	Bogota, Colombia	Olomouc, Czech Rep	Hradec Kralove, Czech Rep	Aarhus, Denmark	Hong Kong China	Cuernavaca, Mexico	Pamplona, Spain	Stoke-on-Trent, UK	Seattle, USA	Baltimore, USA	Total
N	1050	330	223	258	122	272	269	656	329	135	1198	870	5712
Socio-demographics													
Age (years), *M (SD)*	42.8(12.6)	41.8 (12.7)	45.6 (11.8)	38.6 (14.3)	35.8 (13.6)	39.8 (13.8)	42.3 (12.8)	42.2 (12.6)	39.4 (13.4)	43.6 (13.3)	44.2 (10.9)	46.7 (10.7)	43 (12.4)
Missing values n (%)	5 (0.5)	1 (0.3)	0 (0)	6 (2.3)	1 (0.8)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	13 (0.2)
Men, %	48.4	48.5	31.8	36.0	38.5	39.0	40.5	45.7	39.5	46.7	55.0	48.7	46.7
Missing values n (%)	2 (0.2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	2 (0.04)
Educational attainment, *%*													
Less than HS	4.3	27.9	46.6	20.5	14.8	7.4	36.4	43.6	4.3	38.5	1.1	1.8	14.2
HS graduate	32.4	31.2	36.3	38.8	53.3	42.3	23.0	28.7	32.5	45.9	34.8	29.5	33.2
College or more	62.3	40.9	17.0	29.8	26.2	50.4	40.5	27.1	62.6	14.8	63.9	68.4	51.6
Missing values n (%)	11 (1.1)	0 (0)	0 (0)	28 (10.9)	7 (5.7)	0 (0)	0 (0)	4 (0.6)	2 (0.6)	1 (0.7)	2 (0.2)	2 (0.2)	57 (1.0)
Working, *%*	80.3	79.4	60.5	77.9	82.8	75.4	60.6	71.0	76.3	64.4	81.3	83.0	77.2
Missing values n (%)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	9 (3.4)	4 (0.6)	0 (0)	0 (0)	1 (0.1)	0 (0)	14 (0.9)
Married / living with partner, %,	73.0	60.3	61.4	52.3	49.2	69.1	56.1	64.8	57.1	45.2	64.1	60.8	63.1
Missing values n (%)	6 (0.6)	0 (0)	0 (0)	34 (13.2)	8 (6.6)	0 (0)	0 (0)	0 (0)	1 (0.3)	2 (1.5)	0 (0)	4 (0.5)	55 (1.0)
High SES neighbourhood*, %	52.5	52.4	33.2	58.9	66.4	54.8	50.6	50.9	41.3	54.8	51.3	53.2	51.4
High Walkability neighbourhood*, %	50.7	50.3	54.7	69.8	44.3	51.1	53.5	50.6	70.2	22.2	50.3	49.5	51.9
Accelerometer variables**, M (SD)													

	Ghent, Belgium	Curitiba, Brazil	Bogota, Colombia	Olomouc, Czech Rep	Hradec Kralove, Czech Rep	Aarhus, Denmark	Hong Kong China	Cuernavaca, Mexico	Pamplona, Spain	Stoke-on-Trent, UK	Seattle, USA	Baltimore, USA	Total
Valid days of wear time	6.7(1.1)	6.7 (1.0)	6.6 (1.0)	6.2 (1.2)	6.2 (1.4)	7.0 (0.8)	5.9 (1.0)	5.7 (1.0)	6.5 (0.8)	6.6 (1.0)	6.7 (0.8)	6.7 (1.2)	6.5 (1.1)
Wear time (h/day)	14.7 (1.3)	14.0 (1.3)	13.9 (1.2)	13.9 (1.4)	14.2 (1.3)	14.9 (1.1)	14.4 (1.4)	14.0 (1.4)	15.0 (1.1)	14.6 (1.2)	14.7 (1.3)	14.8 (1.4)	14.5 (1.4)
MVPA (min/day)	35.5 (23.5)	31.5 (24.6)	37.0 (26.4)	47.1 (27.7)	45.1 (25.9)	39.7 (23.3)	44.9 (25.3)	31.2 (25.2)	51.0 (29.5)	36.7 (27.3)	36.3 (24.9)	29.2 (22.0)	36.3(25.4)
Sedentary time (min/day)	507 (110)	476 (111)	463 (92)	486 (101)	508 (95)	572 (91)	542 (98)	468 (90)	544 (88)	499 (104)	523 (104)	538 (102)	513 (105)
Perceived neighbourhood attributes, M (SD)													
Residential density	82.6 (72.4)	99.7 (124)	51.7 (59.6)	89.1 (68.6)	85.1 (68.8)	83.5 (63.4)	444 (216)	38.1 (40.9)	187 (102)	36.2 (32.5)	37.5 (53.9)	59.9 (79.4)	86.9 (122)
Missing values n (%)	57 (5.4)	2 (0.6)	0 (0)	34 (13.2)	8 (6.6)	0 (0)	0 (0)	8 (1.2)	0 (0)	15 (11.1)	0 (0)	1 (0.1)	125 (2.2)
Street connectivity	2.7 (0.7)	3.3 (0.7)	3.1 (0.6)	3.0 (0.7)	3.0 (0.6)	3.1 (0.6)	3.2 (0.8)	2.9 (0.5)	3.3 (0.7)	3.1 (0.7)	3.0 (0.8)	3.0 (0.8)	3.0(0.7)
Missing values n (%)	6 (0.6)	0 (0)	0 (0)	30 (11.6)	8 (6.6)	0 (0)	0 (0)	0 (0)	0 (0)	1 (0.7)	1 (0.1)	0 (0)	46 (0.8)
Land use mix - access	3.3 (0.6)	3.6 (0.5)	3.4 (0.4)	3.5 (0.6)	3.4 (0.6)	3.6 (0.6)	3.5 (0.7)	3.3 (0.5)	3.7 (0.5)	3.4 (0.7)	3.2 (0.8)	3.0 (0.8)	3.3 (0.7)
Missing values n (%)	5 (0.5)	0 (0)	0 (0)	27 (10.5)	8 (6.6)	0 (0)	0 (0)	0 (0)	0 (0)	1 (0.7)	0 (0)	0 (0)	41 (0.7)
Land use mix – diversity	3.6 (0.9)	4.1 (0.5)	4.2 (0.4)	3.9 (0.6)	4.0 (0.6)	4.2 (0.6)	4.1 (0.7)	3.7 (0.6)	4.5 (0.4)	3.7 (0.5)	3.8 (0.8)	3.6 (0.9)	3.8 (0.8)
Missing values n (%)	4 (0.4)	0 (0)	0 (0)	24 (9.3)	7 (5.7)	0 (0)	0 (0)	0 (0)	1 (0.3)	0 (0)	0 (0)	0 (0)	36 (0.6)
Infrastructure/ safety for walking	2.8 (0.5)	2.8 (0.8)	2.8 (0.5)	3.1 (0.5)	3.2 (0.5)	3.1 (0.5)	3.4 (0.6)	2.6 (0.4)	3.4 (0.5)	3.2 (0.5)	3.0 (0.6)	3.1 (0.6)	3.0 (0.6)
Missing values n (%)	7 (0.7)	0 (0)	0 (0)	29 (11.2)	8 (6.6)	0 (0)	0 (0)	0 (0)	0 (0)	1 (0.7)	0 (0)	0 (0)	45 (0.8)
Aesthetics	2.6 (0.6)	2.9 (0.8)	2.4 (0.5)	2.4 (0.6)	2.6 (0.5)	2.7 (0.6)	2.8 (0.7)	2.6 (0.5)	2.7 (0.7)	2.3 (0.8)	3.1 (0.7)	3.1 (0.6)	2.8 (0.7)
Missing values n (%)	6 (0.6)	0 (0)	0 (0)	29 (11.2)	8 (6.6)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	46 (0.8)
Traffic safety	2.4 (0.6)	2.4 (0.8)	2.4 (0.5)	2.9 (0.6)	3.1 (0.5)	2.9 (0.5)	2.9 (0.6)	2.4 (0.5)	2.5 (0.7)	2.5 (0.7)	2.7 (0.7)	2.7 (0.7)	2.6 (0.7)
Missing values n (%)	7 (0.7)	0 (0)	0 (0)	30 (11.6)	8 (6.6)	0 (0)	0 (0)	1 (0.2)	0 (0)	0 (0)	0 (0)	0 (0)	46 (0.8)

	Ghent, Belgium	Curitiba, Brazil	Bogota, Colombia	Olomouc, Czech Rep	Hradec Kralove, Czech Rep	Aarhus, Denmark	Hong Kong China	Cuernavaca, Mexico	Pamplona, Spain	Stoke-on-Trent, UK	Seattle, USA	Baltimore, USA	Total
Safety from crime	3.2 (0.5)	2.3 (0.5)	1.9 (0.6)	3.2 (0.6)	3.4 (0.5)	3.3 (0.6)	3.4 (0.7)	2.2 (0.7)	3.6 (0.6)	3.0 (0.7)	3.4 (0.6)	3.4 (0.7)	3.1 (0.8)
Missing values n (%)	7 (0.7)	0 (0)	0 (0)	30 (11.6)	8 (6.6)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1 (0.1)	0 (0)	46 (0.8)
Few cul-de-sacs	3.0 (0.8)	2.9 (1.1)	2.7 (0.8)	2.9 (1.0)	3.0 (0.9)	2.8 (0.9)	3.5 (0.8)	2.6 (0.7)	3.6 (0.9)	2.3 (1.0)	2.8 (1.1)	2.8 (1.2)	2.9 (1.0)
Missing values n (%)	6 (0.6)	0 (0)	0 (0)	30 (11.6)	8 (6.6)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	2 (0.2)	0 (0)	46 (0.8)
Barriers to walking	3.3 (0.7)	3.1 (1.1)	2.9 (0.7)	3.4 (0.8)	3.5 (0.8)	3.7 (0.6)	3.3 (1.0)	2.8 (0.7)	3.6 (0.8)	3.4 (0.8)	3.2 (1.0)	3.8 (0.6)	3.3 (0.9)
Missing values n (%)	8 (0.8)	0 (0)	0 (0)	27 (10.5)	8 (6.6)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	43 (0.8)
BMI (Outcome variable)													
BMI in kg/m^2, *M (SD)*	24.2 (3.9)	26.2 (4.3)	25.5 (4.1)	24.6 (3.9)	24.2 (3.7)	24.2 (4.0)	22.6 (3.4)	28.0 (5.0)	23.9 (3.4)	27.2 (5.1)	26.6 (5.4)	27.2 (5.7)	25.8 (4.9)
Missing values n (%)	28 (2.7)	1 (0.3)	0 (0)	0 (0)	1 (0.8)	0 (0)	2 (0.7)	0 (0)	4 (1.2)	10 (7.4)	0 (0)	5 (0.6)	51 (0.9)
Weight status													
Normal, %	61.2	41.2	51.6	62.4	60.7	65.8	77.0	27.6	66.0	37.8	45.7	37.9	49.8
Overweight, %	28.3	40.0	35.4	28.7	31.1	27.2	19.0	41.0	28.0	30.4	34.1	39.5	33.3
Obese, %	7.8	18.5	13.0	8.9	7.4	7.0	3.3	31.4	4.9	24.4	20.1	22.0	16.1
Missing values, %	2.7	0.3	0.0	0.0	0.8	0.0	0.7	0.0	1.2	7.4	0.0	0.6	0.9

Notes: HS=high school; MVPA = moderate-to-vigorous physical activity; M = mean; SD = standard deviation; n (%) = number and (percentage) of missing values; h = hours; min = minutes; valid days of accelerometer wear are those with 10+ valid hours of wear; SES = socio-economic status; BMI = body mass index

* no missing values.

Table 2.

Associations of perceived neighbourhood attributes with BMI and weight status

	BMI (kg/m^2)			Weight status (normal vs. overweight or obese)		
Perceived neighbourhood attribute measure [theoretical range]	**e^b**	**95% CI**	***p***	**OR**	**95% CI**	***p***
Residential density [0–10]*	0.995	0.989, 1.001	.079	0.898	0.833, 0.968	.005
Street connectivity [1–4]	0.991	0.984, 0.998	.008	0.927	0.852, 1.009	.079
Land use mix-access [1–4]	0.997	0.990, 1.004	.429	0.968	0.884, 1.060	.481
Land use mix-diversity [1–5]	0.990 [0.990]	0.983, 0.997 [0.983, 0.997]	.004 [.004]	0.905	0.831, 0.985	.021
Infrastructure/safety for walking [1–4]	0.991	0.983, 0.999	.040	0.937	0.843, 1.042	.232
Aesthetics [1–4]	0.992	0.984, 0.999	.043	0.985	0.892, 1.087	.759
Traffic safety [1–4]	0.988 [0.991]	0.980, 0.995 [0.984, 0.999]	<.001 [.025]	0.928	0.847, 1.018	.115
Safety from crime [1–4]	0.985 [0.987]	0.977, 0.993 [0.979, 0.995]	<.001 [.002]	0.984	0.889, 1.090	.762
Few cul-de-sacs [1–4]	0.999	0.994, 1.004	.575	0.974	0.915, 1.037	.408
Barriers to walking [1–4]	0.998	0.992, 1.004	.463	0.943	0.876, 1.014	.114
Composite measure - SEV models	0.996	0.994, 0.997	<.001	0.925	0.881, 0.970	.001
Composite measure - MEV models	0.992	0.990, 0.995	<.001	NA	NA	NA

Notes. All models adjusted for gender, smooth of age, marital status, educational attainment, employment status, administrative-unit socio-economic status, city, total number of valid accelerometer wearing days and average number of wearing hours; e^b = antilogarithm of regression coefficient derived from generalised additive mixed model with Gamma variance and logarithmic link functions; CI = confidence intervals; OR = odds ratio; Composite measure - SEV / MEV models = composite measures (sum of z-scores) of perceived environmental attributes significantly related to an outcome in single-environmental-variable / multiple-environmental-variable models; NA = not applicable as no multiple environmental variable models could be defined for weight status.

* Original score ranging from 0 to 1000 divided by 100. Underlined values in square brackets indicate estimates of multiple environmental variable models, which included all perceived environmental attributes that independently contributed to the explanation on an outcome. No multiple environmental variable models could be defined for weight status.

Table 3.

Summary findings of mediation models of associations between perceived neighbourhood attributes (exposure) with BMI

Exposure [theoretical range]	Mediator	(A) Association of exposure with mediator			(B) Association of mediator with BMI			(C) Direct (mediator(s)-adjusted) association of exposure with BMI			Conclusion
		e^b *or b*	95% *CI*	*p*	e^b or *F*-test[1]	95% *CI*	*p*	e^b	95% *CI*	*p*	
Street connectivity [1–4]	MVPA	**1.022**	**1.023, 1.079**	**<.001**	***F*** **(3.84, 5434) = 31.40** (see Fig. S1)		**<.001**	**0.993**	**0.987, 0.999**	**.038**	**Partial mediation**
	Sedentary time	**−3.997**	**−7.266, −0.728**	**.017**	1.000	0.999, 1.001	.118				No mediation
Land use mix diversity [1–5]	MVPA	**1.058**	**1.030, 1.087**	**<.001**	***F*** **(3.84, 5435) = 31.40** (see Fig. S2)		**<.001**	**0.993**	**0.986, 0.999**	**.034**	**Partial mediation**
	MVPA - MEV	**1.059**	**1.031, 1.088**	**<.001**	***F*** **(3.79, 5432) = 31.40** (see Fig. 1)		**<.001**	**0.993**	**0.986, 0.999**	**.032**	**Partial mediation**
	Sedentary time	−0.993	−4.297, 2.310	.555	-[2]	-	-				No mediation
Infrastructure/safety for walking [1–4]	MVPA	**1.060**	**1.025, 1.096**	**<.001**	***F*** **(3.83, 5434) = 31.22** (see Fig. S3)		**<.001**	0.993	0.985, 1.002	.111	**Full mediation**
	Sedentary time	**5.745**	**1.636, 9.856**	**.006**	1.000	0.999, 1.001	.091				No mediation
Aesthetics [1–4]	MVPA	**1.056**	**1.024, 1.088**	**<.001**	***F*** **(3.84, 5434) = 31.68** (see Fig. S4)		**<.001**	0.994	0.986, 1.002	.121	**Full mediation**
	Sedentary time	**−5.465**	**−9.259, −1.671**	**.005**	1.000	0.999, 1.001	.120				No mediation
Traffic safety [1–4]	MVPA	1.018	0.989, 1.048	.218	-[2]	-	-	-[2]	-	-	No mediation
	MVPA - MEV	1.009	0.979, 1.039	.565	-[2]	-	-	-[2]	-	-	No mediation
	Sedentary time	1.093	−2.489, 4.676	.550	-[2]	-	-				No mediation
Safety from crime [1–4]	MVPA	1.026	0.994, 1.059	.110	-[2]	-	-	-[2]	-	-	No mediation
	MVPA - MEV	1.027	0.995, 1.062	.100	-[2]	-	-	-[2]	-	-	No mediation
	Sedentary time	−1.523	−5.434, 2.388	.445	-[2]	-	-				No mediation
Composite measure - SEV models	MVPA	**1.018**	**1.011, 1.024**	**<.001**	***F*** **(3.81, 5434) = 30.11** (see Fig. S5)		**<.001**	**0.997**	**0.995, 0.998**	**<.001**	**Partial mediation**
	Sedentary time	−0.391	−1.176, 0.394	.330	-[2]	-	-				No mediation
Composite measure - MEV models	MVPA	**1.022**	**1.010, 1.033**	**<.001**	***F*** **(3.78, 5434) = 30.72** (see Fig. S6)		**<.001**	**0.993**	**0.991, 0.996**	**<.001**	**Partial mediation**

Exposure [theoretical range]	Mediator	(A) Association of exposure with mediator			(B) Association of mediator with BMI			(C) Direct (mediator(s)-adjusted) association of exposure with BMI			Conclusion
		e^b or b	95% *CI*	*p*	e^b or *F*-test[1]	95% *CI*	*p*	e^b	95% *CI*	*p*	
	Sedentary time	−0.223	−1.631, 1.186	.757	-[2]	-	-				No mediation

Notes. Only perceived neighbourhood attributes that were significantly associated with body mass index were examined. All models adjusted for gender, smooth of age, marital status, educational attainment, employment status, administrative-unit socio-economic status, city, total number of valid accelerometer wearing days and average number of wearing hours; MVPA = moderate-to-vigorous physical activity; MEV = multiple-environmental-variable models; Composite measure -SEV / MEV models = composite measures (sum of z-scores) of perceived environmental attributes significantly related to BMI in single-environmental-variable / multiple-environmental-variable models. e^b = antilogarithm of regression coefficient derived from generalised additive mixed model with Gamma variance and logarithmic link functions (models of MVPA and BMI); CI = confidence intervals; *b* = regression coefficient derived from generalised additive mixed model with Gaussian variance and identity link functions (models of sedentary time). Underlined values indicate estimates of multiple environmental variable models (MEV), which included all perceived environmental attributes that independently contributed to the explanation of body mass index (see Table 2).

[1] *F*-tests of smooth terms are given (rather than regression coefficients) for significant curvilinear relationships; values in brackets represent degrees of freedom and the shapes of the relationships are depicted in the relevant Figures (e.g., Fig. S1).

[2] Estimates not provided because the potential mediator (MVPA and/or sedentary time) were not related to exposure.

Table 4.

Summary findings of mediation models of associations between perceived neighbourhood attributes (exposure) with weight status (normal weight vs. overweight/obese)

Exposure [theoretical range]	Mediator	(A) Association of exposure with mediator			(B) Association of mediator with weight status			(C) Direct (mediator-adjusted) association of exposure with weight status			Conclusion
		e^b* or *b	**95% *CI***	***p***	**OR or *F*-test[1]**	**95% *CI***	***p***	**OR**	**95% *CI***	***p***	
Residential density[3] [0–10]	MVPA	1.022	0.998, 1.046	.069	-[2]	-	-	-[2]	-	-	No mediation
	Sedentary time	**6.697**	**3.916, 9.477**	**<.001**	**1.002**	**1.001, 1.002**	**<.001**	**0.886**	**0.822, 0.956**	**.002**	**Inconsistent mediation**
Land use mix diversity [1–5]	MVPA	**1.058**	**1.030, 1.087**	**<.001**	***F* (2.54, 5435) = 34.61** (see Fig. 2)		**<.001**	0.926	0.852, 1.008	.074	**Full mediation**
	Sedentary time	−0.993	−4.297, 2.310	.555	-[2]	-	-				No mediation
Composite measure - SEV models	MVPA	**1.032**	**1.016, 1.048**	**<.001**	***F* (2.48, 5435) = 25.98** (see Fig. S7)		<.001	**0.936**	**0.892, 0.982**	**.007**	**Partial mediation**
	Sedentary time	**2.017**	**0.176, 3.858**	**.032**	1.000	0.999, 1.001	.114				No mediation

Notes. Only perceived neighbourhood attributes that were significantly associated with weight status were examined. All models adjusted for gender, smooth of age, marital status, educational attainment, employment status, administrative-unit socio-economic status, city, total number of valid accelerometer wearing days and average number of wearing hours; MVPA = moderate-to-vigorous physical activity; Composite measure -SEV models = composite measures (sum of z-scores) of perceived environmental attributes significantly related to weight status in single-environmental-variable models; e^b = antilogarithm of regression coefficient derived from generalised additive mixed model with Gamma variance and logarithmic link functions (models of MVPA); b = regression coefficient derived from generalised additive mixed model with Gaussian variance and identity link functions (models of sedentary time); OR = odds ratio; CI = confidence intervals.

[1] *F*-tests of smooth terms are given (rather than regression coefficients) for significant curvilinear relationships; values in brackets represent degrees of freedom and the shapes of the relationships are depicted in the relevant Figures (e.g., Fig. 2).

[2] Estimates not provided because the potential mediator (MVPA and/or sedentary time) were not related to exposure.

[3] Original score ranging from 0 to 1000 divided by 100.