



Objectively-assessed neighbourhood destination accessibility and physical activity in adults from 10 countries: An analysis of moderators and perceptions as mediators



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ARTICLE INFO

Keywords:

Geographic information systems
Physical activity
Sociodemographic characteristics
Perceived neighbourhood attributes
Walkability
Parks
Public transport
Mediated moderation

ABSTRACT

Rationale: Residents of neighbourhoods with high destination accessibility (higher population density, more-interconnected streets, and better access to services, public transport and parks) are more physically active. Evidence on the factors that underlie these associations is sparse and inconsistent.

Objective: We examined (1) five socio-demographic and four non-destination perceived neighbourhood attributes as moderators of the relationship between objectively-assessed destination accessibility and moderate-to-vigorous physical activity (MVPA); (2) perceived indicators of destination accessibility as mediators of those relationships; and, (3) the generalizability of findings across 14 cities.

Methods: Data were from the International Physical Activity and Environment Network (IPEN) Adult study ($N = 6822$), which provided comparable objective and perceived environmental variables and accelerometer-based MVPA from 14 cities across 10 countries. Mediation and moderation analyses were performed.

Results: Objective net residential density, public transport density, and number of parks in the neighbourhood were consistently associated with MVPA across all examined socio-demographic groups and non-destination perceived neighbourhood characteristics. However, only the association between number of parks and MVPA was mediated by its conceptually-comparable perceived indicator. While the associations of objective intersection density and land use mix with MVPA were moderated by both gender and perceived pedestrian infrastructure/safety, only the latter moderating effects were mediated by the conceptually-comparable perceived indicators. Perceived neighbourhood safety and/or aesthetics moderated the associations of objective ratio of retail/civic land to total area and distance to nearest transport stop with MVPA. These associations were not mediated by the conceptually-comparable perceived indicators.

Conclusion: Densely populated neighbourhoods with access to public transport and parks have the potential to significantly and equitably contribute to adults' MVPA on a global scale. Perceived neighbourhood aesthetics, pedestrian-friendliness and safety can magnify the positive effects of mixed-use neighbourhoods on residents' MVPA by interacting with the perceived ease of access to a variety of destinations.

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1. Introduction

Physical inactivity is one of the main behavioural risk factors contributing to non-communicable diseases and premature mortality worldwide (Lee et al., 2012). Whilst acknowledging that a myriad of interacting factors influence physical activity (PA), there is a strong case for the creation of neighbourhood environments that facilitate engagement in active transport and recreational physical activity (PA) as a promising strategy for improving global public health (Kohl et al., 2012; Barnett et al., 2017). Identifying neighbourhood built environment attributes that promote PA is important because neighbourhoods represent universal daily life centres that can be shaped by healthy evidence-based urban planning and transportation policies and practices. Numerous studies have shown that residents of “accessible” neighbourhoods typified by high population density, interconnected streets, and better access to public transport and a variety of services tend to be more physically active than their counterparts (Bauman et al., 2012; Sallis et al., 2016). Destination accessibility is important for PA across multiple domains. Having shops, services and public transit within walking or biking distance is essential for facilitating active transportation (Sallis et al., 2016; Cerin et al., 2017). Easy access to parks and other recreation facilities has been associated with more leisure-time PA (Bauman et al., 2012).

Using objective measures and common methods across 10 countries, the International Physical Activity and Environment Network (IPEN) Adult study has provided evidence that the relation of destination accessibility to PA was similar in different geographical locations and cultures (Sallis et al., 2016). However, the extent to which these relations and their underlying mechanisms are generalizable across socio-demographic groups and neighbourhoods differing in other activity-friendly features (e.g., safety) remains largely unexplored (Van Dyck et al., 2015). Questions of mediation and moderation of neighbourhood destination accessibility and PA relations represent important knowledge gaps. These issues have been seldom studied despite ecological models of health behaviours positing that PA is influenced by the interplay of individual, psychological, socio-cultural, policy and environmental factors (Sallis et al., 2008).

Socio-demographic characteristics including age (Cerin et al., 2013d; Villaneuva et al., 2014; Van Dyck et al., 2015), gender (Forsyth et al., 2009; Cerin et al., 2016b, 2017a), educational attainment (Forsyth et al., 2009; Cerin et al., 2013d; Perez et al., 2018) and employment status (Cerin et al., 2017a) have all been found to moderate, albeit inconsistently, associations between indicators of neighbourhood destination accessibility and PA. The discrepancy in findings is likely due to unaccounted residential self-selection bias, the use of different environmental and PA measures, lack of statistical power to detect moderating effects, and differences between cultures and socio-demographic groups in discrepancies between objective measures and perceptions of the environment, and/or biases in measures of perceptions of the environment. A robust evaluation of socio-demographic moderators of destination accessibility-PA associations needs to be based on large-scale studies that provide comparable objective environmental and PA data from various economically, culturally- and physically-diverse locations. It is particularly important to focus on objective exposure and outcome measures, since differences in the interpretation of self-report instruments gauging perceived environmental attributes (King et al., 2004) and PA (Cerin et al., 2016a) may yield spurious divergences in effects across countries and socio-demographic groups. For example, in the IPEN Adult study, the level of correspondence between objectively-assessed and self-reported PA differed by country, age, gender, employment status and educational attainment (Cerin et al., 2016a). Thus, detection of significant socio-demographic moderators of associations between environmental attributes and self-reported PA could be due to reporting biases rather than to genuine differences in effects.

Two studies of socio-demographic moderators of destination

accessibility and objectively-assessed PA relations have been undertaken using pooled multi-country data. One focused on perceptions of the neighbourhood environment (Van Dyck et al., 2015), while the other examined engagement in moderate-to-vigorous PA (MVPA) at different times of the day and days of the week (Cerin et al., 2017a). Socio-demographic moderators of associations between objectively-assessed indicators of destination accessibility and total objectively-assessed MVPA are yet to be identified. Other characteristics of the environment that can potentially moderate relations between MVPA and destination accessibility, including neighbourhood safety, pedestrian infrastructure and aesthetics, also remain understudied. Although there is some evidence that destination accessibility is more strongly related to PA in neighbourhoods with better neighbourhood safety and pedestrian infrastructure (Cerin et al., 2013b, 2013c; Bracy et al., 2014), the evidence is scarce, based on single-country data from high-income countries and mostly related to older adults. There is also a dearth of evidence about the mechanisms responsible for these moderating effects.

One mechanism by which objective aspects of destination accessibility may differentially influence PA across socio-demographic groups and various environmental conditions is perception of the environment. Objective environmental conditions are often expected to affect PA through one's perceptions. However, the level of agreement between objective and perceived measures of conceptually-comparable aspects of the environment is typically low (Brownson et al., 2009). This is because perceptions result from the integration of objective information captured through the senses with personal histories and cognitive and affective factors (e.g., attitudes, preferences) (Nassar, 2008; Orstad et al., 2017). Thus, differences in objective environmental features-PA associations across socio-demographic groups and environmental conditions (e.g., safety) may be in part due to differences in perceptions. Alternatively, different associations may be due to the same perceptions having different effects on PA in different subgroups of people.

An understanding of the extent to which socio-demographic and environmental moderators of the associations between objective destination accessibility and PA are due to differences in perceptions or salience of these attributes for PA is important for the development of effective interventions encompassing modifications of the built environment and/or behavioural strategies to enhance residents' perceptions. Hence, the aims of the present study were to: (1) estimate associations between objectively-assessed indicators of destination accessibility and objectively-assessed MVPA among adults from 14 cities across 10 countries, adjusted for perceived neighbourhood safety, pedestrian infrastructure and aesthetics; (2) identify socio-demographic and non-destination perceived environmental (neighbourhood safety, pedestrian infrastructure, and aesthetics) moderators of associations between objectively-assessed indicators of destination accessibility and MVPA; (3) examine the extent to which these associations and moderating effects are explained (mediated) by perceived measures of aspects of the neighbourhood environment that are *conceptually-comparable* to the objective measures of destination accessibility; (4) and examine whether moderators and mediators of associations are generalizable across cities.

Based on theoretical considerations (Nassar, 2008) and prior findings (Van Dyck et al., 2015; Sallis et al., 2016; Barnett et al., 2017; Cerin et al., 2017a), we hypothesised that socio-demographic characteristics and non-destination perceived neighbourhood environment conditions would moderate associations of objective indicators of destination accessibility with objectively-assessed MVPA; specifically, older, non-employed, male participants and those reporting better neighbourhood environmental conditions were expected to show stronger positive associations. As illustrated in Fig. 1, we expected the objective destination accessibility—MVPA associations and moderating effects to be in part mediated by *conceptually-matched* measures of perceived destination accessibility (e.g., perceived land-use mix). Given the lack of empirical evidence, we did not formulate specific hypotheses

regarding whether moderating effects would be explained by differences in perceptions or by differences in effects of perceived measures of destination accessibility on MVPA. Finally, we hypothesised that the above associations, moderators and mediators would be generalizable across countries.

2. Method

2.1. Study design and participants

We used data from IPEN Adult, a multi-country cross-sectional epidemiological study on environmental correlates of adults' PA and obesity (Kerr et al., 2013). Ten countries collected objective MVPA and neighbourhood environmental data between 2002 and 2011. These were Belgium (Ghent), Brazil (Curitiba), Colombia (Bogotá), the Czech Republic (Olomouc), Denmark (Aarhus), China (Hong Kong), Mexico (Cuernavaca), New Zealand (North Shore, Waitakere, Wellington and Christchurch), the UK (Stoke-on-Trent) and the USA (Baltimore-Washington DC and Seattle). Participants were recruited using a two-stage stratified sampling strategy to maximise variability in neighbourhood walkability and socio-economic status (SES) and balance participant recruitment by walkability and SES. Neighbourhood-level SES was determined using census data, while neighbourhood walkability index scores were created for small administrative units in each city using Geographic Information Systems (GIS) data. In each city, neighbourhoods were classified into high/low walkable by high/low SES strata. A balanced number of participants were recruited from each stratum by identifying households in the selected neighbourhoods and inviting an adult member of the household to complete a survey and wear an accelerometer. To account for seasonality effects on PA, seven of the 10 countries collected data across all seasons in a balanced manner across neighbourhood types. Denmark and the UK collected data in Spring/Summer, when participants were more likely to engage in outdoor PA. Brazil collected data in a single season (Spring) because Curitiba has relatively homogeneous average temperatures and humidity levels across the year. Details of participant recruitment and response rates

have been published elsewhere (Kerr et al., 2013). Ethical approval was obtained in each country from the principal investigator's institutional review board, and all participants provided written informed consent prior to data collection.

This study included participants aged 18–66 years from 14 cities that collected objective environmental and MVPA measures (N = 10,008). Among these, 2739 participants did not wear an accelerometer because they did not consent or the investigators could not afford collecting objective MVPA data on all participants. Being younger, unemployed and without a college degree (all *ps* < .01) were associated with a higher likelihood of non-wearing an accelerometer. Of the remaining 7269 participants, 447 did not provide valid accelerometer data. The latter tended to be younger and lower educated (all *ps* < .01) than their counterparts. Socio-demographic and environmental characteristics of the sample of 6822 participants included in this study are reported in [Supplementary Tables 1 and 2](#).

2.2. Measures

2.2.1. Objectively-assessed MVPA (outcome variable)

Accelerometers were used to objectively estimate average minutes of MVPA per day. This study focused on MVPA because it is the PA intensity advocated by the World Health Organisation's recommendations on PA for health (World Health Organization, 2010). Ten cities used an ActiGraph accelerometer, while the four New Zealand cities used the Actical. Participants were instructed to wear the accelerometer for 7 days around the waist during waking hours when not engaging in water activities (e.g., showering). Vertical axis data aggregated to 1-min epochs and expressed as counts per minute (cpm) were used for estimating MVPA. Non-wear time was defined as ≥ 60 min of consecutive zero cpm, valid days had ≥ 10 h of wear time and participants with ≥ 4 valid wear days (at least one weekend day and three weekdays) were considered to have valid accelerometer data. ActiGraph data were converted to mean minutes of MVPA per valid day using Freedson's cut point of ≥ 1952 cpm (Freedson et al., 1998). For Actical data, we developed a ≥ 730 cpm cut point for moderate intensity PA to

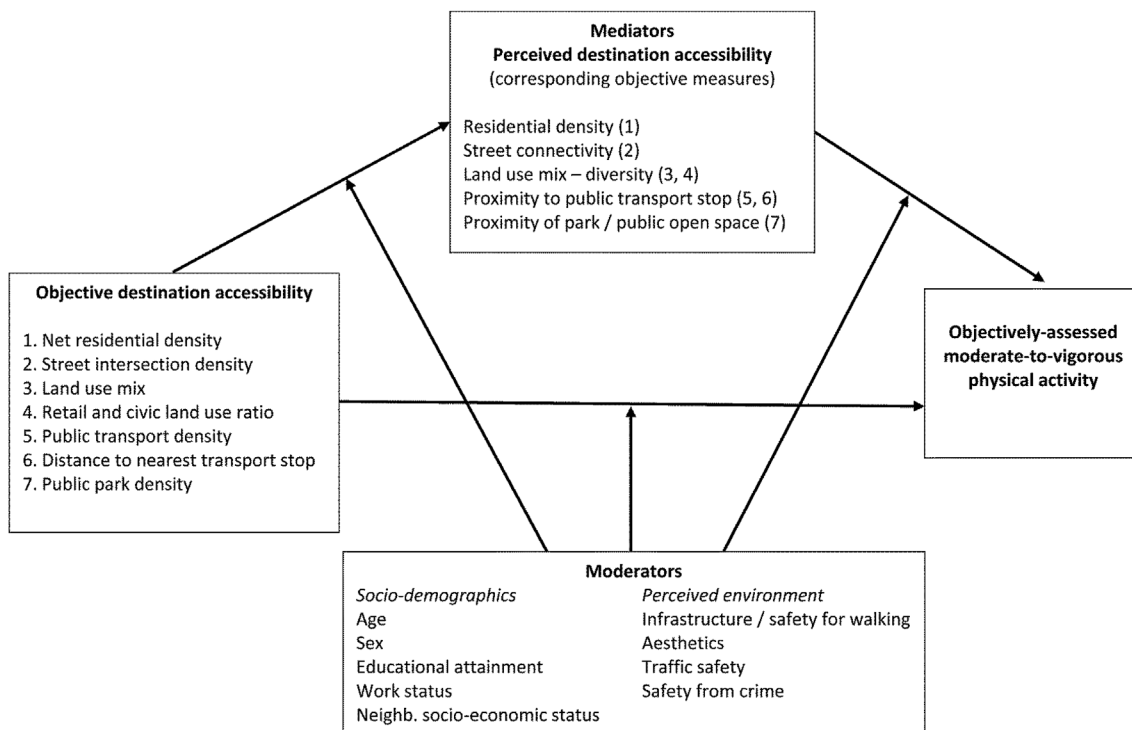


Fig. 1. Conceptual model of associations between objective neighbourhood destination accessibility and objectively-assessed moderate-to-vigorous physical activity mediated by perceived destination accessibility and moderated by socio-demographic and perceived environmental factors.

enable comparison with the ActiGraph estimates (Cerin et al., 2017a). For each participant, we computed the average minutes of MVPA per day (outcome variable).

2.2.2. Objective indicators of destination accessibility (exposure variables)

GIS templates were developed to guide the computation of objective indicators of destination accessibility and to ensure cross-site comparability (Adams et al., 2014). Neighbourhoods were defined as 0.5-km and 1-km street-network buffers around participants' residential addresses, and indicators were computed for each buffer. The selection of the buffer sizes was based on evidence about the typical distances that adults walk from home in low-density countries (Burke and Brown, 2007). In this study, the following indicators of destination accessibility were examined: net residential density (number of dwellings/km²); intersection density (number of ≥3-arm intersections/km²); land use mix (an entropy score ranging from 0 to 1 and based on residential, retail and civic land uses); ratio of retail and civic land area contained or intersected by residential buffer to total buffer area; public transport density (number of public transport stops/km²); public park density (number of public parks contained or intersected by a buffer); and street-network distance to nearest transport stop (metres). In the present analyses, we used whichever buffer size was shown to yield the strongest association with MVPA.

2.2.3. Perceived neighbourhood environment (mediators and moderators)

We collected information on participants' perceptions of the neighbourhood environment using the Neighbourhood Environment Walkability Scale (NEWS) adapted for multi-country studies to maximise cross-country score comparability (Cerin et al., 2013a). This study used the following NEWS subscales and items conceptually comparable to the objective indicators of destination accessibility: Residential density; Street connectivity; Land use-mix diversity; Proximity of public transport stop; Proximity of park/public open space. The above NEWS variables were considered conceptually-comparable mediators of associations between the corresponding objective indicators of destination accessibility and MVPA (Fig. 1). Scores on the residential density subscale represented a weighted sum of items reflecting perceived dwelling density with scores ranging from 0 to 1000. Land use mix – diversity scores reflected average perceived walking proximity from home to nine types of destinations. Items were rated on a 5-point scale ranging from ≤5 min (assigned a value of 5, greater proximity) to >30 min walking (assigned a value of 1). Proximity of public transport stop and park/public open space were items in the land use mix – diversity subscale that also were analysed separately. Street connectivity scores represented average ratings of items answered using a 4-point Likert scale.

Four other NEWS subscales that were not oriented toward accessibility of neighbourhood destinations were considered as potential moderators of the associations between the objective destination accessibility and MVPA. These were Infrastructure/safety for walking; Aesthetics; Traffic safety; and Safety from crime. These subscales' items were rated on a 4-point Likert scale, and average ratings were computed for each subscale. Subscales and items were scored in a direction consistent with higher ratings denoting more PA-friendly features.

2.2.4. Socio-demographic characteristics (moderators and covariates)

Socio-demographic covariates were age (in years); gender (men; women); educational attainment (less than high school; high school graduate; college or higher); employment status (working; not working); neighbourhood-level SES (high; low); and marital status (single; couple). All socio-demographic characteristics were also considered as potential moderators with the exception of marital status.

2.3. Statistical analysis

Descriptive statistics were computed for the whole sample ($N = 6822$) 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 moderation, mediation, and mediated moderation effects. GAMMs are generalized linear mixed models with a linear predictor including nonlinear forms of one or more explanatory variables defined by smooth functions. GAMMs were used because they can accommodate outcomes with various distributional assumptions and estimate curvilinear dose-response relationships of unknown form using smooth terms. Separate sets of GAMMs were estimated for each objective indicator of destination accessibility.

Analyses were conducted in four steps. We first estimated the associations (linear or curvilinear) of objective indicators of destination accessibility (exposures; X in the regression equations below) with MVPA (outcome; Y) adjusted for city, socio-demographic characteristics [covariates (Co) and moderators (Mod)] and perceived infrastructure/safety for walking, aesthetics, traffic safety, and safety from crime (Mod) (main effect GAMMs; step 1). Curvilinear relations of objective indicators of destination accessibility with the logarithm of the expected value of MVPA were estimated using smooth terms in GAMMs, which were modelled using thin plate splines (Woods, 2006). Smooth terms failing to provide sufficient evidence of a curvilinear relation (on the basis of Akaike Information Criterion [AIC] as described below) were replaced by simpler linear terms. We added appropriate two-way interaction terms to the main effect GAMMs to identify city, socio-demographic and perceived environmental moderators of associations ($X:Mod$) and three-way interaction terms to examine possible between-city heterogeneity in moderation effects (step 2). We also included a three-way gender by employment status by objective environment interaction term because, in a prior study, employment status moderated the associations between land use mix and MVPA differently in men and women (Cerin et al., 2017a). The significance of the moderation effects was evaluated by comparing standard AIC values of models with and without a specific interaction term. Moderation effects were deemed significant if the inclusion of the interaction term in the model yielded a > 5-unit smaller AIC than the main effect or simpler interaction model. The same criterion applied for the determination of the significance of curvilinear (vs. linear) relationship (Burnham and Anderson, 2002).

We examined mediation effects if no moderators were identified in step 2, and mediated moderation effects if moderators were identified. This was done by first regressing a perceived indicator of destination accessibility (mediator; M) onto the conceptually-corresponding objective indicator (X), covariates (Co) and, when appropriate, the interaction between the objective indicator and the moderators ($X:Mod$) identified in step 2 (step 3). In the final step 4 of the analyses, we regressed MVPA (Y) onto the objective (X) and conceptually-comparable perceived indicator of destination accessibility (M), covariates (Co) and, when appropriate, the interaction terms of both objective ($X:Mod$) and perceived indicators of destination accessibility ($M:Mod$) with the moderators identified in step 2. The four analytical steps are depicted by the following regression equations (key regression terms underlined):

Step 1 – effect of objective indicator of destination accessibility (exposure) on MVPA (b_1)

$$Y = \text{Intercept}_1 + \underline{b_1(X)} + b_2(\text{Mod}) + b_3(\text{Co}) + e_1$$

Step 2 – moderators of effect of objective indicator of destination accessibility on MVPA (b_6)

$$Y = \text{Intercept}_2 + b_4(X) + b_5(\text{Mod}) + \underline{b_6(X:Mod)} + b_7(\text{Co}) + e_2$$

Step 3 – effect of objective indicator of destination accessibility (b_8) and its moderators (b_{10}) on comparable perceived indicator of

destination accessibility (mediator)

$$M = \text{Intercept}_3 + \underline{b_8(X)} + b_9(\text{Mod}) + \underline{b_{10}(X \cdot \text{Mod})^*} + b_{11}(\text{Co}) + e_3$$

Step 4 – exposure-adjusted effect of mediator (b_{13}) and its moderators (b_{16}) on MVPA, and indirect effect of exposure (b_{12}) and its moderators (b_{15}) on MVPA

$$Y = \text{Intercept}_4 + \underline{b_{12}(X)} + \underline{b_{13}(M)} + b_{14}(\text{Mod}) + \underline{b_{15}(X \cdot \text{Mod})^*} + \underline{b_{16}(M \cdot \text{Mod})^*} + b_{17}(\text{Co}) + e_4$$

Where $e_1 \dots 4$ are error terms, $b_1 \dots 17$ are regression coefficients and the interaction terms with an asterisk (*) are included when b_6 is statistically significant.

As the commonly-recommended product-of-coefficient test of mediation is not available for GAMMs, we used the joint-significance test to determine mediation and moderated mediation (Mackinnon and Luecken, 2008). According to this test, mediation is confirmed if both b_8 and b_{13} regression coefficients (or curvilinear effects) are statistically significant. Mediated moderation is confirmed when both b_{10} and b_{13} are statistically significant and/or both b_8 and b_{16} are statistically significant (Muller et al., 2005).

Significant moderation effects were probed by estimating associations at meaningful values of the moderators (categories for categorical moderators and $M \pm 1SD$ for continuous moderators). Continuous and ordinal independent and moderator variables were centered around their mean prior to analysis. GAMMs of daily minutes of MVPA and perceived residential density used gamma variance and logarithmic link functions, as these variables were positively skewed. The antilogarithms of their regression coefficients are interpreted as the proportional increase in the outcome variables following a 1-unit increase in the predictor. The remaining GAMMs used Gaussian variance and identity link functions. As only 4.3% of participants had missing data on socio-demographic or environmental variables, regression analyses were performed on complete cases. All analyses were conducted in R (R Core Team, 2015) using the packages ‘mgcv’ (Wood, 2006) and ‘multcomp’ (Bretz et al., 2010).

3. Results

On average, participants accumulated 37.3 min of MVPA per day (Supplementary Table 1). MVPA was positively linearly associated with objective intersection density, public transport density, and number of

Table 1
Associations of objective indicators of destination accessibility (OIDA) with accelerometer-assessed moderate-to-vigorous physical activity ($N = 6526$).

	e^b	95% CI	<i>p</i>
Main effects of OIDA			
Net residential density – 1 km bf (1000 dwellings/km ²)	$F(1.92, 6202) = 7.35^{\S}$ (see Fig. 2)		< .001
Intersection density – 1 km bf (100 intersections/km ²)	1.063	1.005, 1.124	.032
Land use mix – 1 km bf (rescaled range 0–10)	1.003	0.994, 1.012	.450
Retail/civic land area to total buffer area ratio - 1 km bf	1.053	0.962, 1.154	.263
Public transport density (10 stops/km ²) – 1 km bf	1.037	1.018, 1.056	< .001
Distance to nearest public transport stop (100 m)	1.003	0.999, 1.007	.082
Number of parks contained or intersected by 0.5 km bf	1.010	1.000, 1.021	.045
Significant interaction effects of OIDA by Moderator ≠ Association in/at ...			
Intersection density by Gender			
men	1.121	1.049, 1.197	< .001
women	1.024	0.964, 1.089	.440
Intersection density by Perceived pedestrian infrastructure/safety (PPIS)			
– 1 SD from the mean of PPIS (2.35)	1.035	0.973, 1.101	.279
mean PPIS (2.92)	1.071	1.011, 1.135	.020
+ 1 SD from the mean of PPIS (3.49)	1.108	1.032, 1.190	.005
Land use mix by Gender by Work status			
non-working men	1.024	1.001, 1.049	.048
working men	1.003	0.991, 1.015	.643
non-working women	0.992	0.975, 1.010	.395
working women	1.004	0.992, 1.016	.488
Land use mix by Perceived pedestrian infrastructure/safety (PPIS)			
– 1 SD from the mean of PPIS (2.35)	0.996	0.987, 1.005	.475
mean PPIS (2.92)	1.004	0.997, 1.012	.341
+ 1 SD from the mean of PPIS (3.49)	1.012	1.003, 1.022	.033
Retail/civic land area to total buffer area ratio by Perceived traffic safety (PTS)			
– 1 SD from the mean of PTS (1.98)	0.943	0.844, 1.054	.389
mean PTS (2.62)	1.026	0.950, 1.109	.585
at + 1 SD from the mean of PTS (3.25)	1.116	1.018, 1.224	.035
Distance to nearest public transport stop by Perceived aesthetics (PAs)			
– 1 SD from the mean of PAs (2.14)	0.999	0.995, 1.004	.809
mean PAs (2.81)	1.003	0.999, 1.006	.150
+ 1 SD from the mean of PAs (3.48)	1.006	1.002, 1.010	.008
Distance to nearest public transport stop by Perceived safety from crime (PSC)			
– 1 SD from the mean of PSC (2.30)	1.001	0.997, 1.005	.533
mean PSC (3.04)	1.003	1.000, 1.007	.070
+ 1 SD from the mean of PSC (3.79)	1.005	1.001, 1.010	.018

Notes. bf = buffer; SD = standard deviation; e^b = antilogarithm of regression coefficient, to be interpreted as the proportional increase in moderate-to-vigorous physical activity with a 1 unit increase in the OIDA; CI = confidence intervals. Numbers in brackets in section reporting interaction effects are values of the moderator. All regression coefficients adjusted for respondents' age, gender, marital status, education, work status, accelerometer wear time, administrative-unit socio-economic status and perceived neighbourhood environmental conditions (e.g., pedestrian infrastructure/safety). ≠ Based on > 5-unit difference in Akaike Information Criterion values. § Significant curvilinear relationship: F-test of smooth term is reported rather than regression coefficients; values in brackets represent degrees of freedom.

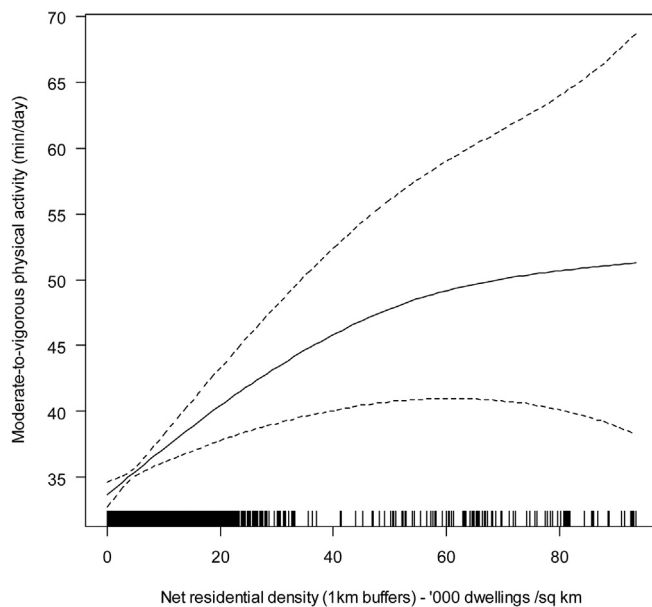


Fig. 2. Relationship between objective net residential density and accelerometer-assessed moderate-to-vigorous physical activity. Dashed lines represent 95% confidence intervals.

parks near home (Table 1), and curvilinearly related to net residential density (Fig. 2) after adjustment for perceived infrastructure/safety for walking, aesthetics, traffic safety, and safety from crime.

3.1. Moderators of associations between objective indicators of destination accessibility and MVPA

We found no significant moderators of objective net residential density, public transport density and number of parks (Supplementary Table 3), while the associations of MVPA with objective intersection density, land use mix, retail/civic land area to total buffer area and distance to nearest public transport were moderated by one or more variables (Table 1). Gender moderated the association of objective intersection density with MVPA, whereby men showed a positive association and women did not (Table 1). Gender and work status moderated the association of land use mix with MVPA, with only non-working men exhibiting a significant positive association. Intersection density, land use mix, ratio of retail/civic land area to total area, and distance to the nearest public transport stops were positively related to MVPA only in those who reported more favourable perceptions of the neighbourhood environment (i.e., higher levels of safety, aesthetics and/or pedestrian infrastructure) (Table 1). Age, educational attainment, neighbourhood SES and city did not moderate any of the examined associations (Supplementary Table 3).

3.2. Mediators and mediated moderation of associations between objective indicators of destination accessibility (exposures) and MVPA

Perceived indicators of destination accessibility mediated the associations (main effects) of three out of seven conceptually-comparable objective indicators with MVPA (Table 2). These were objective land use mix, ratio of retail/civic land area to total area, and number of parks near one's home. Although the first two objective indicators did not show a significant main effect on MVPA (Table 1), the data supported their positive association with MVPA through perceptions. In fact, both objective indicators were significantly associated with perceived land use mix – diversity (Table 2; column A) and, in turn, perceived land use mix – diversity was positively associated with MVPA after adjusting for the matching objective indicators of destination accessibility (Table 2; column B). Perceived proximity of park/public

open space mediated the positive association between objective number of parks and MVPA. The four objective indicators for which there was insufficient evidence of a mediated main effect showed strong curvilinear positive associations with their conceptually-comparable perceived indicators (Table 2; Fig. 3). However, the relevant perceived indicators were not significantly associated with MVPA after adjustment for their objective counterparts, which is a condition for mediation (Table 2; column B).

Only two of the seven identified moderating effects (Table 1) were explained by the examined mediating process (Table 2). This was because there was no significant interaction of a specific mediator (perceived indicator of destination accessibility) with a moderator, or the mediator was not related to MVPA. Mediated moderation was supported for the effects of perceived pedestrian infrastructure/safety on the associations of objective intersection density and land use mix with MVPA. Both objective indicators were positively linearly or curvilinearly (Fig. 3B) associated with their corresponding perceived indicator (Table 2; column A). Also, the associations of the relevant perceived indicators with MVPA were moderated by perceived pedestrian infrastructure/safety (Table 2; column B). After adjustment for these moderating effects, perceived pedestrian infrastructure/safety was no longer a significant moderator of the associations between objective intersection density, land use mix and MVPA (Table 2; column C).

4. Discussion

This study examined socio-demographic characteristics and perceived neighbourhood conditions that moderate the associations of objective indicators of destination accessibility with objectively-assessed MVPA in adults from 14 cities across 10 countries. It also identified perceived indicators of destination accessibility that may mediate these associations and moderating effects.

4.1. Objective indicators of destination accessibility with no moderators

Objective residential density, public transport density and number of parks in the neighbourhood were consistently positively associated with MVPA across all examined socio-demographic groups, perceived neighbourhood conditions and cities. Though these findings are similar to a previous study (Sallis et al., 2016), the present findings provide further evidence that these urban design features consistently support PA in adults irrespective of difference in culture, SES, and perceptions of the neighbourhood environment. Residential density is necessary to create and support a large variety of local commercial services and a widespread and affordable public transport network (Frank, 2000) that, in turn, promote walking for transport (Christiansen et al., 2016; Cerin et al., 2017b). Parks in the neighbourhood facilitate engagement in leisure-time PA (Schipperijn et al., 2017) and also walking for transport to/from parks (Christiansen et al., 2016).

Only the association of number of parks in the neighbourhood with MVPA was mediated by its conceptually-comparable perceived indicator. As expected, residents with one or more parks in their neighbourhood perceived the closest park to be more proximal to their homes as compared to residents with no parks (Fig. 3F), and the resulting perceived proximity of a park, in turn, contributed to higher levels of MVPA (Table 2, column B). The fact that such mediating effects were not observed for objective residential and public transport densities is likely due to the metric characteristics of the corresponding perceived indicators (mediators) and/or the inability to examine car ownership as a moderator. Specifically, the NEWS perceived residential density subscale showed a high level of measurement error in urban environments with > 6000 dwellings/km² (Fig. 3A). This subscale was originally developed for use in relatively low-density US cities, and items were subsequently added to capture higher density in cities such as Hong Kong (Cerin et al., 2013a). However, these items may not be sufficiently sensitive to differences at the higher end of the density

Table 2
Summary findings of mediation and mediated moderation models of associations between objective indicators of destination accessibility (exposures) and accelerometer-assessed moderate-to-vigorous physical activity (MVPA).

Exposure – Mediator	(A) Association of exposure with mediator and moderators of association			(B) Association of mediator with MVPA and moderators of association			(C) Direct (mediator-adjusted) association of exposure with MVPA and moderator of association		
	95% CI	p	e ^b or ΔAIC [#]	95% CI	p	e ^b or ΔAIC [#]	95% CI	p	
Objective net residential density – Perceived residential density MEDIATION models <i>F</i> (8.58, 6,196) = 49.32 [§] (see Fig.3A) <i>F</i> (1.94, 6,202) = 8.58 [§] (see Suppl. Fig. 1)		< .001	0.999	0.999, 1.000	.717	1.058	0.999, 1.120	< .001	
<i>Conclusion:</i> No mediation.									
Objective intersection density – Perceived street connectivity MEDIATION models <i>F</i> (5.89, 6,199) = 25.00 [§] (see Fig.3B) <i>F</i> (1.049, 1,198) = 8.58 [§] (see Suppl. Fig. 1)		< .001	1.019	0.991, 1.047	.188	1.058	0.999, 1.120	.052	
<i>Conclusion:</i> No mediation.									
MEDIATED MODERATION models Moderator: Gender association in men association in women <i>Conclusion:</i> No mediated moderation. Moderator: Perceived pedestrian infrastructure / safety (PPIS) association at -1SD from mean of PPIS association at mean PPIS association at +1 SD from mean of PPIS	ΔAIC = -10.84 - - ΔAIC = -4.52 - - -		ΔAIC = 0.99 - - ΔAIC = 5.93 0.998 1.021 1.045	0.965, 1.033 0.993, 1.049 1.008, 1.083	.912 .133 .017	ΔAIC = 12.12 1.121 1.028 ΔAIC = -1.01 - - -	1.049, 1.198 0.966, 1.093 - - -	< .001 .387 - - -	
<i>Conclusion:</i> Mediated moderation: association of exposure with mediator and moderating effect of PPIS on mediator-MVPA association are both significant.									
Objective land use mix – Perceived land use - diversity MEDIATION models <i>F</i> (0.082, 0.091) = 0.073, 0.091 <i>F</i> (1.044, 1.074) = 0.073, 0.091		< .001	1.044	1.016, 1.074	.002	0.999	0.990, 1.008	.850	
<i>Conclusion:</i> Mediation: association of exposure with mediator and association of mediator with MVPA are both significant									
MEDIATED MODERATION models Moderator: Gender by Work association in non-working men association in working men association in non-working women association in working women <i>Conclusion:</i> No mediated moderation. Moderator: Perceived pedestrian infrastructure / safety (PPIS) association at -1SD from mean of PPIS association at mean PPIS association at +1 SD from mean of PPIS	ΔAIC = -68.10 - - - - ΔAIC = 0.53 - - -		ΔAIC = 1.42 - - - - ΔAIC = 6.52 1.027 1.052 1.077	0.993, 1.061 1.023, 1.081 1.036, 1.119	.115 < .001 < .001	ΔAIC = 11.05 1.020 0.999 0.988 0.999 ΔAIC = 1.71 - - -	1.000, 1.040 0.987, 1.010 0.971, 1.005 0.987, 1.011 - - -	.050 .859 .181 .916 - - -	
<i>Conclusion:</i> Mediated moderation: association of exposure with mediator and moderating effect of PPIS on mediator-MVPA association are both significant.									

(continued on next page)

Table 2 (continued)

Exposure – Mediator	(A) Association of exposure with mediator and moderators of association				(B) Association of mediator with MVPA and moderators of association				(C) Direct (mediator-adjusted) association of exposure with MVPA and moderator of association			
	<i>b</i>	95% CI	<i>p</i>	or <i>F</i> -test [§] or $\Delta AIC^{\#}$	<i>e^b</i>	95% CI	<i>p</i>	or $\Delta AIC^{\#}$	<i>e^b</i>	95% CI	<i>p</i>	or <i>F</i> -test [§] or $\Delta AIC^{\#}$
Objective retail/civic land to total buffer area ratio – Perceived land use mix - diversity MEDIATION models	<i>F</i> (4.83, 6,200) = 57.84 [§] (see Fig.3C)											
	< .001											
Conclusion: Mediation: association of exposure with mediator and association of mediator with MVPA are both significant												
MEDIATED MODERATION models												
Moderator: Perceived traffic safety (PTS)	$\Delta AIC = -15.10$											
association at -1SD from mean of PTS	-											
association at mean PTS	-											
association at +1 SD from mean of PTS	-											
Conclusion: No mediated moderation.												
Objective public transport density – Perceived proximity of public transport stop MEDIATION models	<i>F</i> (7.85, 6,197) = 25.44 [§] (see Fig.3D)											
	< .001											
Conclusion: No mediation.												
Objective distance to nearest public transport stop - Perceived proximity of public transport stop MEDIATION models	<i>F</i> (7.43, 6,197) = 62.34 [§] (see Fig.3E)											
	< .001											
Conclusion: No mediation.												
MEDIATED MODERATION models												
Moderator: Perceived crime safety (PCS)	$\Delta AIC = 17.13$											
association at -1SD from mean of PCS	-0.032											
association at mean PCS	-0.041											
association at +1 SD from mean of PCS	-0.050											
Conclusion: No mediated moderation.												
Moderator: Perceived aesthetics (PAs)	$\Delta AIC = 7.07$											
association at -1SD from mean of PAs	-0.037											
association at mean PAs	-0.041											
association at +1 SD from mean of PAs	-0.044											
Conclusion: No mediated moderation.												
Objective number of parks – Perceived proximity of park / public open space MEDIATION models	<i>F</i> (5.48, 6,199) = 20.91 [§] (see Fig.3F)											
	< .001											
Conclusion: Mediation: association of exposure with mediator and association of mediator with MVPA are both significant												

Notes: *b* = regression coefficient; *e^b* = antilogarithm of regression coefficient; *F* = *F*-ratio; *CI* = confidence intervals; ΔAIC = difference in Akaike Information Criterion values. All regression coefficients adjusted for respondents' age, gender, marital status, education, work status, accelerometer wear time, administrative-unit (neighbourhood) socio-economic status and perceived neighbourhood environmental conditions (pedestrian infrastructure/safety; aesthetics; traffic safety; safety from crime). [§] Significant curvilinear relationship: *F*-test of smooth term is reported rather than regression coefficients; values in brackets represent degrees of freedom. Significant associations (*p* < .05) are in bold. [#] significant test for moderation effects only (> 5-unit difference in *AIC*).

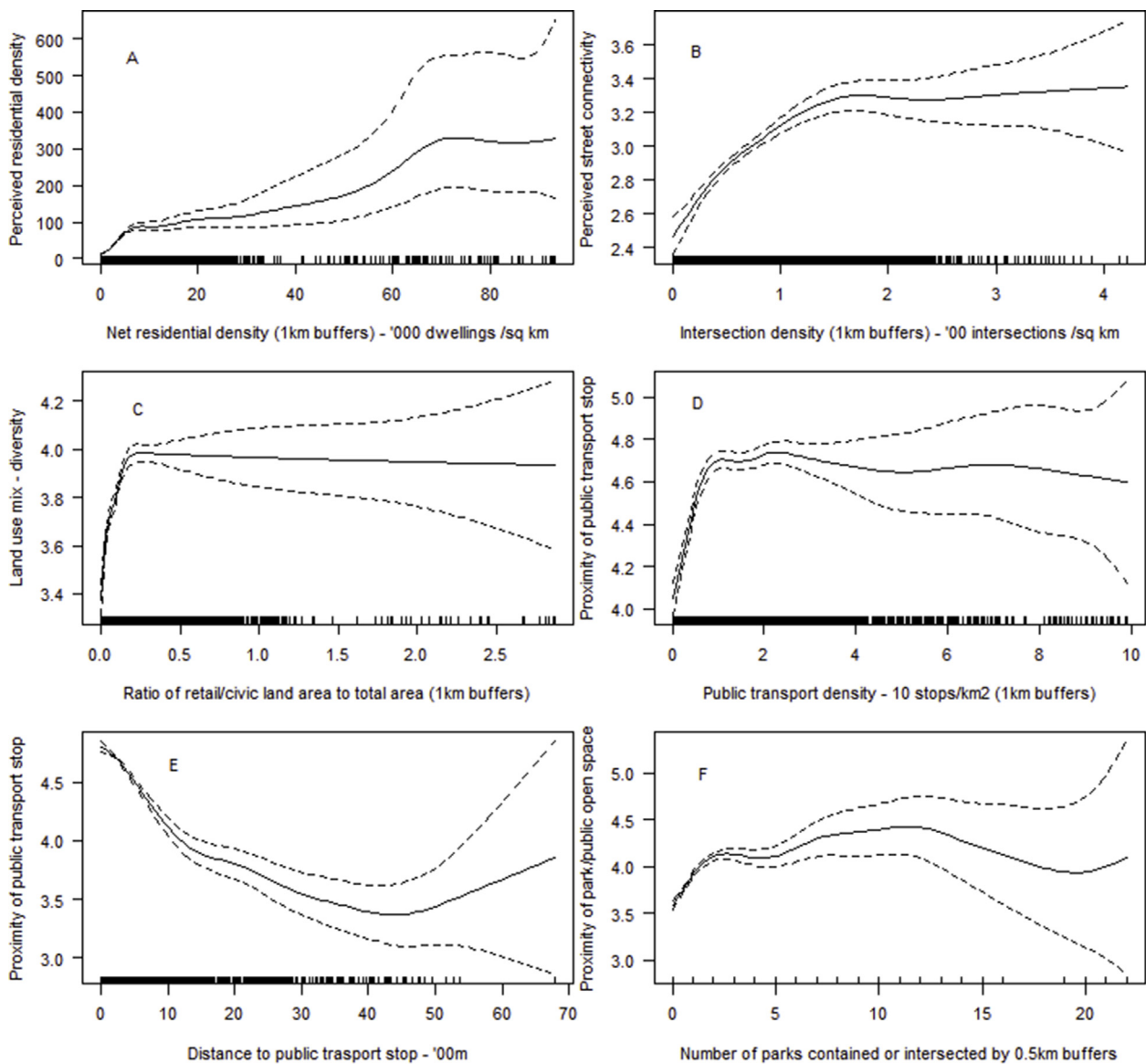


Fig. 3. Relationships between objective indicators of destination accessibility and conceptually-comparable perceived indicators of destination accessibility. Dashed lines represent 95% confidence intervals.

spectrum, or respondents may be unable to provide accurate ratings on these high-density items. Thus, measurement error might have contributed to failing to detect a significant association between perceived residential density and MVPA, which is a condition for mediation.

Perceived proximity of public transport showed restricted variability in responses, with 91% of participants reporting a public transport stop within 10-min walk from home. This might have attenuated its association with MVPA. Yet, as perceived proximity of public transport showed adequate levels of correspondence with its objective counterparts (Fig. 3D and E), it is also possible that density rather than proximity of public transport exerted a stronger influence on MVPA. In fact, it is plausible to assume that the availability of more transport stops in the neighbourhood would increase the likelihood of residents' walking to a public transport stop that meets their needs (Sallis et al., 2016).

4.2. Objective indicators of destination accessibility with moderators

Objective intersection density, land use mix, ratio of retail/civic

land area to total buffer area, and distance to nearest public transport stop did not show independent main effects on MVPA in the whole sample. However, they were positively associated with MVPA in certain socio-demographic groups or specific perceived neighbourhood conditions. Also, objective land use mix and ratio of retail/civic land area to total buffer area were found to have a positive indirect effect on MVPA through perceived land use mix, which acted as a mediator (Table 2). Mediation analyses based on the joint-significance test can sometimes detect mediated effects when there is insufficient evidence of an exposure-outcome link due to the link being causally distal and, therefore, weak (Shrout and Bolger, 2002; Fritz and MacKinnon, 2007). This is especially the case when the mediator (here, perceived land use mix) explains in full the effect of the exposure (objective land use mix) on the outcome (MVPA) (Fritz and MacKinnon, 2007), as appears to have occurred in our study. Indeed, compared to psychosocial factors (e.g., self-efficacy for PA), neighbourhood environment attributes represent causally distal influences on PA (Nassar, 2008). However, environment attributes impact on a large number of people for a sustained amount of time and, therefore, are of substantial public health significance.

4.3. Socio-demographic moderators

Objective intersection density was positively related to MVPA only in men, and land use mix only in non-working men. Although both objective attributes were strongly related to their perceived counterparts, these moderating effects were not mediated by their corresponding perceived indicators. Other mechanisms may be responsible for the observed findings. For example, high levels of intersection density and land use mix are often accompanied by higher traffic volumes/hazards that women tend to perceive as barriers for PA (Boone-Heinonen and Gordon-Larsen, 2011). Thus, differences in perceptions of traffic hazards may account for between-gender differences in associations of objective intersection density and land use mix with MVPA. Further, mixed-use neighbourhoods may influence MVPA to a greater extent in non-working than working men because the former have more discretionary time for walking in the neighbourhood. This pattern of associations may not be found in relation to perceived land use mix due to reverse causation. Walkers living in mixed-use neighbourhoods, irrespective of their work status, may report higher levels of perceived land use mix than non-walkers because they are more aware of their environment.

The fact that we found only two differences in objective environment-MVPA associations between socio-demographic groups, and that these were similar across cities, suggests that environmental interventions targeting the examined indicators of destination accessibility would yield similar positive effects across entire adult populations on a global scale. These conclusions are also supported by the dearth of socio-demographic moderators found in multi-country studies using perceived indicators of destination accessibility (Van Dyck et al., 2015; Perez et al., 2018).

4.4. Perceived neighbourhood conditions as moderators

Objective intersection density and land use mix were positively related to MVPA only if neighbourhoods were perceived to have good pedestrian infrastructure/safety. Similarly, objective ratio of retail/civic land area to total buffer area was positively related to MVPA only in those reporting high levels of neighbourhood traffic safety. The first two moderating effects were completely mediated by their corresponding perceived indicators showing significant interaction effects with perceived pedestrian infrastructure/safety on MVPA. These findings suggest that objective intersection density and land use mix affect residents' perceptions of the same environment attributes and these perceptions, in turn, affect MVPA only in those who also perceive to be living in a safe neighbourhood with better pedestrian infrastructure. To promote PA, well-interconnected, mixed-use neighbourhoods also need to be pedestrian-friendly and safe. The very few studies that examined aspects of pedestrian infrastructure and traffic safety as moderators of destination accessibility-PA associations observed similar synergistic effects (Cerin et al., 2013b, 2013c; Bracy et al., 2014). The introduction of permanent or part-time pedestrianised zones, traffic-calming features and crosswalk/sidewalk improvements in destination-rich, mix-use urban areas may significantly contribute to increasing adult residents' PA (Smith et al., 2017).

Distance to the nearest public transport stop was positively related to MVPA only in those reporting higher levels of neighbourhood environmental aesthetics and safety from crime. Residents may be more likely to use public transport and walk to a transit point if their neighbourhood is safe and aesthetically pleasing (Lu et al., 2018). The fact that the degree of correspondence between objective distance and perceived proximity of public transport was higher in respondents with higher scores on perceived aesthetics and safety from crime speaks in favour of this supposition. Under such conditions, assuming that a public transport stop meets the residents' needs, those with a stop far from home will walk more and, hence, accumulate more MVPA than those with a stop near home. This observed moderating effect was not

mediated by perceived proximity of public transport probably due to the restricted variability in proximity ratings.

4.5. Strengths and weaknesses

Apart from addressing novel research questions of public health significance, a study strength was the utilisation of comparable objective environmental and PA data from 14 cities across 10 culturally- and physically-diverse countries. This study provides findings that can inform national as well as international strategies for the promotion of PA. The application of statistical models capable of estimating complex curvilinear associations within the context of mediation analysis is another study strength that helped gain new insights into the relationships between objective and perceived aspects of the neighbourhood environment.

The cross-sectional nature of the mediational analyses is a study limitation. Cross-sectional studies preclude the establishment of causation and temporal precedence of effects (from the objective environment to perceptions to behaviour). Although randomised controlled trials in this research field are not feasible, quasi-experimental and long-term longitudinal studies are needed to clarify the magnitude and direction of examined effects. A recent report from the US Guide to Community Preventive Services found both quasi-experimental and cross-sectional studies similarly supported a recommendation that combinations of built environment interventions improved PA (The Community Guide, 2018). The sampling strategy adopted in this study was designed to maximise within-city variability in built environmental exposures and, hence, the city-specific samples were not representative of the respective adult populations. The inability to account for climatic conditions, neighbourhood self-selection, car ownership and several other socio-demographic characteristics might have contributed to confounding. Despite efforts to standardise methods, response rates, accelerometers and survey data collection procedures somewhat varied across cities. This may have introduced different types of biases across study sites. Finally, the conceptual correspondence between some pairs of objective and perceived indicators of destination accessibility was not strong.

5. Conclusions

Positive, albeit relatively weak, associations of objective neighbourhood net residential density, public transport density, and number of parks near one's home with accelerometer-assessed MVPA were consistent across socio-demographic groups and perceived neighbourhood conditions across 14 cities from 10 countries. These environmental attributes have the potential to significantly and equitably contribute to adults' PA on a global scale. Other objective indicators of destination accessibility were positively associated with MVPA only among residents reporting favourable perceptions of neighbourhood safety, pedestrian infrastructure or aesthetics. This pattern of findings suggests that mixed-use neighbourhoods with easy access to destinations need to be pedestrian-friendly and safe to have a positive impact on residents' PA. Perceived access to destinations mediated just over a third of the observed associations and moderating effects. Future research needs to establish whether the failure to observe more consistent perception-mediated effects of various objective indicators of destination accessibility on MVPA might be due to measurement limitations associated with ceiling effects in self-reports, conceptual mismatch between objective and perceived measures of destination accessibility (distance to vs. density of destinations), or the presence of other mediating mechanisms.

Data statement

The dataset supporting the conclusions of this article is available upon reasonable request to the international coordinating centre of the IPEN study.

Acknowledgments

Data collection in Hong Kong was supported by the grants (#HKU740907H and #747807H) and the HKU URC Strategic Research Theme (Public Health). US data collection and Coordinating Center processing was supported by the following NIH grant: R01 CA127296 (NCI). The study conducted in Bogota was funded by COLCIENCIAS grant 519 2010, Fogarty and CeIBA (Center in Complex-Systems, Basic and Applied Research at the Universidad de los Andes). Ester Cerin is supported by an Australian Research Council Future Fellowship (FT3 #140100085). The contributions of Neville Owen were supported by a NHMRC Program Grant (#569940), a NHMRC Senior Principal Research Fellowship (#1003960), and by the Victorian Government's Operational Infrastructure Support Program. The Danish study was partly funded by the Municipality of Aarhus. Data collection in the Czech Republic was supported by the grant of Ministry of Education, Youth and Science (# MSM 6198959221). Data collection in New Zealand was supported by the Health Research Council of New Zealand grant # 07/356. Data collection in Mexico was supported by the Club Foundation which received an unrestricted training grant from The Coca-Cola Company. Data collection in the UK was funded partly under the National Prevention Research Initiative, managed by the Medical Research Council (Grant Id 75376).

Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.socscimed.2018.06.034>.

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