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Associations of built environment and proximity of food outlets with weight status: Analysis from 14 cities in 10 countries

Thomas Cochrane[a,*], Yan Yu[a,b], Rachel Davey[a], Ester Cerin[c,d], Kelli L. Cain[e,c], Terry L. Conway[e,c], Jacqueline Kerr[e], Lawrence D. Frank[f,g], James E. Chapman[g], Marc A. Adams[h], Duncan Macfarlane[i], Delfien Van Dyck[j,k], Poh-Chin Lai[l], Olga L. Sarmiento[m], Jens Troelsen[n], Deborah Salvo[o,p], Rodrigo Reis[q,r], Josef Mitáš[s], Grant Schofield[t], Neville Owen[u], James F. Sallis[c,e]

[a] Centre for Research & Action in Public Health, University of Canberra, Canberra, Australia
[b] Therapeutic Goods Administration, Department of Health, Australia
[c] Mary MacKillop Institute for Health Research, Australian Catholic University, Melbourne, Australia
[d] School of Public Health, University of Hong Kong, Hong Kong, China
[e] Family Medicine and Public Health, University of California San Diego, USA
[f] School of Community and Regional Planning, University of British Columbia, Vancouver, Canada
[g] Urban Design 4 Health, Rochester, New York, USA
[h] College of Health Solutions, Arizona State University, Phoenix, USA
[i] Centre for Sports and Exercise, University of Hong Kong, Hong Kong, China
[j] Department of Movement and Sports Sciences, Ghent University, Belgium
[k] Research Foundation Flanders, Belgium
[l] Department of Geography, University of Hong Kong, Hong Kong, China
[m] School of Medicine, Universidad de los Andes, Bogota, Colombia
[n] Institute of Sports Science and Clinical Biomechanics, University of Southern Denmark, Odense, Denmark
[o] Prevention Research Center in St. Louis & Center for Diabetes Translation Research, Brown School, Washington University in St. Louis, USA
[p] Center for Nutrition and Health Research, National Institute of Public Health of Mexico, Cuernavaca, Mexico
[q] Prevention Research Center in St. Louis, Brown School, Washington University in St. Louis, St. Louis, USA
[r] Graduate Program in Urban Management (PPGTU), Pontifical Catholic University of Paraná (PUCPR), Curitiba, Brazil
[s] Institute of Active Lifestyle, Faculty of Physical Culture, Palacký University, Olomouc, Czech Republic
[t] Human Potential Centre, Auckland University of Technology, New Zealand
[u] Behavioural Epidemiology Laboratory, Baker Heart and Diabetes Institute, Melbourne, Australia

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ABSTRACT

The study aimed to examine associations of neighborhood built environments and proximity of food outlets (BE measures) with body weight status using pooled data from an international study (IPEN Adult). Objective BE measures were calculated using geographic information systems for 10,008 participants (4463 male, 45%) aged 16–66 years in 14 cities. Participants self-reported proximity to three types of food outlets. Outcomes were body mass index (BMI) and overweight/obesity status. Male and female weight status associations with BE measures were estimated by generalized additive mixed models. Proportion (95% CI) of overweight (BMI 25 to < 30) ranged from 16.6% (13.1, 19.8) to 41.1% (37.3, 44.7), and obesity (BMI ≥ 30) from 2.9% (1.3, 4.4) to 31.3% (27.7, 34.7), with Hong Kong being the lowest and Cuernavaca, Mexico highest for both proportions. Results differed by sex. Greater street intersection density, public transport density and perceived proximity to restaurants (males) were associated with lower odds of overweight/obesity (BMI ≥ 25). Proximity to public transport stops (females) was associated with higher odds of overweight/obesity. Composite BE measures were more strongly related to BMI and overweight/obesity status than single variables among men but not women.

* Correspondence to: Thomas Cochrane, Centre for Research & Action in Public Health, Health Research Institute, University of Canberra, University Drive South, Canberra 2617, Australia.

E-mail addresses: Tom.Cochrane@canberra.edu.au (T. Cochrane), Yan.Yu@health.edu.au (Y. Yu), rachel.davey@canberra.edu.au (R. Davey), Ester.Cerin@acu.edu.au (E. Cerin), kcain@ucsd.edu (K.L. Cain), tlconway@ucsd.edu (T.L. Conway), jkerr@grantdoctor.org (J. Kerr), ldfrank@ud4h.com (L.D. Frank), jchapman@urbandesign4health.com (J.E. Chapman), marc.adams@asu.edu (M.A. Adams), djmac@hku.hk (D. Macfarlane), delfien.vandyck@ugent.be (D. Van Dyck), pclai@hku.hk (P.-C. Lai), osarmien@uniandes.edu.co (O.L. Sarmiento), JTroelsen@health.sdu.dk (J. Troelsen), dsalvo@wustl.edu (D. Salvo), reis.rodrigo@wustl.edu (R. Reis), josef.mitas@upol.cz (J. Mitáš), grant.schofield@aut.ac.nz (G. Schofield), Neville.Owen@baker.edu.au (N. Owen), jsallis@ucsd.edu (J.F. Sallis).

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One standard deviation improvement in the composite measures of BE was associated with small reductions of 0.1–0.5% in BMI but meaningful reductions of 2.5–5.3% in the odds of overweight/obesity. Effects were linear and generalizable across cities. Neighborhoods designed to support public transport, with food outlets within walking distance, may contribute to global obesity control.

1. Introduction

Elevated body mass index (BMI) is associated with multifaceted risks to health (GBD 2015 Risk Factors Collaborators, 2016) and higher health care costs (Kent et al., 2017). The rapid increase in international prevalence of overweight/obesity over recent decades (Finucane et al., 2011) is likely explained predominantly by global economic, technological, and environmental changes influencing unhealthy lifestyle choices (Swinburn et al., 2011). Numerous calls for action have been made (Centers for Disease Control and Prevention, 2005; WHO, 2013) and considerable research effort has been committed to try to reverse the upward trend in prevalence of overweight and obesity, but little progress is evident (Roberto et al., 2015).

Whereas traditional psychological models of obesity posit only psychological and social influences, contemporary obesity prevention approaches are based on multi-level ecological models (Sallis & Owen, 2008) and the concept that environmental and policy changes that facilitate healthier choices and complement individual interventions are promising for sustainable population changes (Swinburn et al., 2011; Centers for Disease Control and Prevention, 2005; Roberto et al., 2015). The present study focuses on the built environment (BE) level of influence, that has received significant research attention. The existing science has been summarized for physical activity by Ding & Gebel (2012) and for eating by Cobb et al. (2015) Reviews noted wide variation in methods among country-specific studies, which prevented estimation of pooled effects, and limited variation in BE, which reduced the ability to detect effects and could explain conflicting findings. Ding & Gebel (2012) recommended strengthening future BE research by conducting studies in more countries with varying urban forms to enhance generalizability of findings.

De Bourdeaudhuij et al. (2015) examined the strength, direction, and shape of associations between perceived neighborhood BE attributes and weight status using pooled data from 12 countries participating in the International Physical Activity and the Environment Network (IPEN) Adult study. In the analyses reported here, we extend that work by examining associations between the same adiposity measures (BMI and overweight/obesity status) using the subset of participants from 14 cities (10 countries) in the IPEN Adult study which had data on objective BE measures and perceived proximity to various types of food outlets.

2. Subjects and methods

2.1. Study design and selection of participants

IPEN Adult was a multi-country cross-sectional study that used a common protocol to collect information on BE, physical activity, weight, and height. Twelve countries (17 cities) participated: Australia (Adelaide), Belgium (Ghent), Brazil (Curitiba), Colombia (Bogota), Czech Republic (Olomouc and Hradec Kralove), Denmark (Aarhus), China (Hong Kong), Mexico (Cuernavaca), New Zealand (North Shore, Waitakere, Wellington, Christchurch), Spain (Pamplona), the UK (Stoke-on-Trent) and USA (Seattle, Washington DC/Baltimore regions). Current analyses used pooled data from 14 cities, excluding Adelaide, Pamplona and Hradec Kralove because one or more of the BE measures was not available.

To maximize variations in BE, participants in each city were recruited across four neighborhood types defined by walkability (high vs. low) and socioeconomic status (SES, high vs. low). A city-specific walkability index was developed for purposes of neighborhood selection from the z-scores of geographic information systems (GIS) measures of net residential density, mixed land use, and intersection density (Frank et al., 2010), and the SES indicator used census-based measures from local administrative-unit boundaries (Kerr et al., 2013). Recruitment within selected areas was conducted by mail, phone, or personal visits. Study dates ranged from 2002 to 2011, with each country typically recruiting over one year. For methodological details, see Kerr et al. (2013).

All investigators received approval under their country's ethical requirements, and all participants provided informed consent. The pooled data study met the NIH Fogarty International Center ethical requirements.

2.2. Measures: objective and perceived BE

Objective GIS variables used in analyses were developed for buffer areas within 0.5 km and 1.0 km of each individual's home address, reachable by the street network. These are common buffer sizes for active transport research as these distances can be covered by a 10–15-minute walk. Variables were analysed in their original units (e.g., number of intersections per km^2), so they were not standardized. Attempts were made to enhance and evaluate the cross-country comparability of the measures through developing GIS templates for core BE constructs and documenting deviations. Details about GIS data sources for each country, comparability evaluation, and GIS measures have been published (Adams et al., 2014).

In this paper, we used the following seven GIS variables considered adequately comparable across countries: residential density, intersection density, land use mix, ratio of retail and civic land area to total buffer area, public transport stop density, street network distance to nearest public transport stop or station, and number of parks contained in or intersected by the buffer (park density). Buffer-specific analysis was conducted, but as the findings were generally similar, results are presented for the 1 km buffer only, except for park density where the 500 m buffer was used due to stronger associations.

Because of variations across countries in land use codes, it was not possible to use GIS-based food source variables. Thus, the food environment was measured by perceived proximity of food outlets, taken from the validated Neighborhood Environment Walkability Scale (Saelens et al., 2003). Survey participants' perceived proximity to the nearest supermarket, other food/grocery store, and restaurant was reported in five ranges: walking time > 30 min (1), 21–30 min (2), 11–20 min (3), 6–10 min (4) and 1–5 min (5). Table 1 presents descriptive statistics for the BE measures for all 14 cities combined and for each city.

We further generated composite measures of single BE attributes that were associated with weight in the same direction, regardless of statistical significance. As the purpose of our analysis was not to reduce variables but capture the overall BE-weight association in the data, we used simple averaging to create composite variables. Three sets of composite measures were constructed: objective GIS-based environments, perceived proximity of food outlets, and a combination of objective and perceived measures.

2.3. Measures: sociodemographic covariates and weight outcomes

Body weight and height were objectively measured in half of the cities (Brazil, Mexico, four New Zealand cities, UK) and self-reported in

Table 1
Descriptive statistics of built environment attributes, objective GIS-based and perceived measures, IPEN Adult study.

	All 14 cities	Ghent Belgium	Curitiba Brazil	Bogota Colombia	Olomouc Czech Republic	Aarhus Denmark	Hong Kong
GIS measures							
Residential density (per km²)–1.0 km buffer							
Mean	7403	7938	6046	8694	18,224	7373	52,702
SD	12,865	6829	4082	3983	10,714	5898	27,868
IQR	1661–7704	1526–12,975	3855–6955	5996–11,897	9215–24,772	2201–12,446	21,236–78,310
NA	36	3	0	0	0	0	15
(%)	(0.36)	(0.26)	(0.00)	(0.00)	(0.00)	(0.00)	(3.14)
Intersection density (per km²)–1.0 km buffer							
Mean	87	84	76	206	66	82	123
SD	66	62	17	96	20	23	55
IQR	42–106	41–92	64–83	130–286	52–79	72–98	81–161
NA	36	3	0	0	0	0	15
(%)	(0.36)	(0.26)	(0.00)	(0.00)	(0.00)	(0.00)	(3.14)
Land use mix–1.0 km buffer							
Mean	0.49	0.56	0.59	0.57	0.62	0.78	0.80
SD	0.27	0.29	0.17	0.20	0.19	0.24	0.21
IQR	0.28–0.68	0.30–0.78	0.49–0.71	0.40–0.74	0.49–0.75	0.61–0.97	0.66–0.95
NA	41	3	0	0	0	0	15
(%)	(0.41)	(0.26)	(0.00)	(0.00)	(0.00)	(0.00)	(3.14)
Ratio of retail and civic land area to total buffer area–1.0 km buffer†							
Mean	0.17	0.14	0.16	0.12	0.06	0.51	0.52
SD	0.24	0.13	0.10	0.08	0.05	0.42	0.24
IQR	0.04–0.20	0.04–0.25	0.10–0.20	0.05–0.16	0.02–0.07	0.16–0.80	0.26–0.68
NA	36	3	0	0	0	0	15
(%)	(0.36)	(0.26)	(0.00)	(0.00)	(0.00)	(0.00)	(3.14)
Public transport density (per km²)–1.0 km buffer							
Mean	15.4	9.4	25.9	2.1	13.4	9.4	10.3
SD	12.6	6.3	7.3	2.6	5.5	4.7	8.4
IQR	5.7–22.3	4.0–15.4	20.8–29.3	0.0–3.4	9.0–17.7	5.5–12.9	2.2–15.8
NA	42	3	0	0	0	0	16
(%)	(0.42)	(0.26)	(0.00)	(0.00)	(0.00)	(0.00)	(3.35)
Street network distance to nearest transport stop or station (m)							
Mean	478.7	313.2	185.0	1673.8	270.9	307.5	584.7
SD	743.9	278.3	117.5	1419.6	175.0	238.6	563.0
IQR	128.7–452.5	144.0–359.3	93.6–252.8	505.7–3306.1	160.9–363.7	146.3–396.6	209.2–728.8
NA	42	3	0	0	0	0	16
(%)	(0.42)	(0.26)	(0.00)	(0.00)	(0.00)	(0.00)	(3.35)

(*continued on next page*)

Table 1 (*continued*)

	All 14 cities	Ghent Belgium	Curitiba Brazil	Bogota Colombia	Olomouc Czech Republic	Aarhus Den-mark	Hong Kong
Number of parks contained or intersected by buffer of 0.5 km							
Mean	7.1	3.8	5.9	27.8	3.6	4.6	12.0
SD	9.2	3.6	4.6	13.5	4.3	3.5	9.5
IQR	2.0–8.0	1.0–6.0	2.0–8.0	15.0–39.0	1.0–5.0	2.0–7.0	5.0–16.0
NA	35	3	0	0	0	0	15
(%)	(0.35)	(0.26)	(0.00)	(0.00)	(0.00)	(0.00)	(3.14)
Perceived walking time to food outlets							
Supermarkets							
Mean	3.4	3.1	3.6	4.4	3.4	4.3	3.9
SD	(1.3)	(1.3)	(1.1)	(0.9)	(1.1)	(1.0)	(1.3)
IQR	3–5	2–4	3–5	4–5	3–4	4–5	3–5
NA	60	10	0	0	38	1	1
(%)	(0.60)	(0.86)	(0.00)	(0.00)	(11.52)	(0.16)	(0.21)
Other grocery stores							
Mean	4.4	4.4	4.6	4.9	4.4	4.6	4.4
SD	(0.9)	(0.9)	(0.6)	(0.4)	(0.8)	(0.7)	(0.9)
IQR	4–5	4–5	4–5	5–5	4–5	4–5	4–5
NA	48	6	0	0	37	0	0
(%)	(0.48)	(0.51)	(0.00)	(0.00)	(11.21)	(0.00)	(0.00)
Restaurants (any type)							
Mean	4.1	3.5	4.1	4.8	4.1	4.4	4.1
SD	(0.9)	(1.3)	(1.1)	(0.6)	(1.0)	(0.9)	(1.1)
IQR	3–5	3–5	4–5	5–5	4–5	4–5	3–5
NA	59	15	0	0	39	0	0
(%)	(0.59)	(1.29)	(0.00)	(0.00)	(12)	(0.00)	(0.00)

	Cuerna-vaca Mexico	North Shore NZ	Wait-akere NZ	Welling-ton, NZ	Christ-church NZ	Stoke-on-Trent, UK	Seattle USA	Balti-more USA
GIS measures								
Residential density (per km^2)–1.0 km buffer								
Mean	2227	1781	2029	4650	1678	4863	3085	2507
SD	934	839	730	5617	375	1551	3687	2326
IQR	1583–2727	1611–1924	1537–2469	1529–6190	1450–2012	3895–6021	1315–3206	809–3937
NA	17	0	0	1	0	0	0	0
(%)	(2.51)	(0.00)	(0.00)	(0.20)	(0.00)	(0.00)	(0.00)	(0.00)
Intersection density (per km^2)–1.0 km buffer								
Mean	145	26	28	44	35	99	71	55
SD	47	7	10	16	6	34	23	28
IQR	111–166	22–31	25–31	35–54	33–40	76–122	56–85	38–67
NA	17	0	0	1	0	0	0	0
(%)	(2.51)	(0.00)	(0.00)	(0.20)	(0.00)	(0.00)	(0.00)	(0.00)
Land use mix–1.0 km buffer								
Mean	0.40	0.37	0.44	0.51	0.35	0.29	0.38	0.39
SD	0.20	0.20	0.27	0.25	0.21	0.19	0.23	0.22
IQR	0.28–0.56	0.21–0.51	0.22–0.59	0.27–0.76	0.19–0.45	0.13–0.44	0.23–0.51	0.20–0.54
NA	17	0	5	1	0	0	0	0
(%)	(2.51)	(0.00)	(0.98)	(0.20)	(0.00)	(0.00)	(0.00)	(0.00)

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Table 1 (*continued*)

	Cuerna-vaca Mexico	North Shore NZ	Wait-akere NZ	Welling-ton, NZ	Christ-church NZ	Stoke-on-Trent, UK	Seattle USA	Balti-more USA
Ratio of retail and civic land area to total buffer area–1.0 km buffer†								
Mean	0.17	0.12	0.11	0.29	0.16	0.04	0.08	0.12
SD	0.12	0.30	0.14	0.49	0.28	0.04	0.06	0.13
IQR	0.07–0.27	0.04–0.14	0.03–0.11	0.05–0.30	0.03–0.13	0.01–0.06	0.04–0.10	0.04–0.17
NA	17	0	0	1	0	0	0	0
(%)	(2.51)	(0.00)	(0.00)	(0.20)	(0.00)	(0.00)	(0.00)	(0.00)
Public transport density (per km^2)–1.0 km buffer								
Mean	29.0	18.8	9.6	16.6	16.4	25.8	16.0	16.9
SD	24.4	7.3	7.3	8.4	9.2	8.2	9.8	13.5
IQR	11.2–38.4	13.9–24.4	4.7–13.5	11.9–21.7	9.8–20.5	19.4–31.5	9.0–22.8	7.6–24.6
NA	22	0	0	1	0	0	0	0
(%)	(3.25)	(0.00)	(0.00)	(0.20)	(0.00)	(0.00)	(0.00)	(0.00)
Street network distance to nearest transport stop or station (m)								
Mean	499.6	248.3	330.4	223.8	294.7	200.2	375.0	633.7
SD	653.3	208.8	259.4	290.5	241.0	134.2	429.4	1011.0
IQR	103.2–601.7	98.9–343.1	134.3–456.2	60.6–296.1	104.0–411.6	100.2–273.2	127.3–447.1	116.2–540.1
NA	22	0	0	1	0	0	0	0
(%)	(3.25)	(0.00)	(0.00)	(0.20)	(0.00)	(0.00)	(0.00)	(0.00)
Number of parks contained or intersected by buffer of 0.5 km								
Mean	1.5	12.0	8.6	4.8	5.5	3.0	3.9	2.4
SD	2.1	6.1	4.0	2.6	2.5	1.6	2.9	2.1
IQR	0.0–2.0	8.0–14.0	6.0–11.0	3.0–7.0	3.0–7.0	2.0–4.0	1.0–6.0	1.0–3.0
NA	17	0	0	0	0	0	0	0
(%)	(2.51)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Perceived walking time to food outlets								
Supermarkets								
Mean	2.6	2.7	2.8	3.3	3.3	3.0	3.7	3.3
SD	(1.2)	(1.3)	(1.3)	(1.1)	(1.1)	(1.2)	(1.1)	(1.2)
IQR	1–3	1–4	2–4	3–4	3–4	2–4	3–5	3–4
NA	0	0	0	0	0	7	2	1
(%)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.83)	(0.16)	(0.11)
Other grocery stores								
Mean	4.8	4.4	4.1	4.5	4.4	4.4	4.1	4.0
SD	(0.6)	(0.8)	(1.0)	(0.8)	(0.8)	(0.9)	(1.1)	(1.1)
IQR	5–5	4–5	4–5	4–5	4–5	4–5	3–5	3–5
NA	0	0	0	0	0	5	0	0
(%)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.59)	(0.00)	(0.00)

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Table 1 (*continued*)

	Cuerna-vaca Mexico	North Shore NZ	Wait-akere NZ	Welling-ton, NZ	Christ-church NZ	Stoke-on-Trent, UK	Seattle USA	Balti-more USA
Restaurants (any type)								
Mean	4.2	4.1	3.6	4.3	4.2	4.1	4.0	3.7
SD	(1.0)	(1.0)	(1.1)	(0.9)	(0.9)	(1.1)	(1.1)	(1.3)
IQR	4–5	3–5	3–5	4–5	4–5	4–5	3–5	3–5
NA	0	0	0	0	0	9	0	0
(%)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(1.07)	(0.00)	(0.00)

GIS geographical information system; SD standard deviation; IQR interquartile range; NA not available (missing data); five categories for perception variables: > 30 min' walk (1), 21–30 min' walk (2), 11–20 min' walk (3), 6–10 min' walk (4) and 1–5 min' walk (5); †two cases from North Shore, NZ and one from Aarhus, Denmark with values of > 3.1 were assigned the value of 3.1.

the others. We calculated BMI as weight (kg) divided by height (m) squared. Using standard cut-offs (WHO, 2000), we classified BMI into normal/lean weight (BMI < 25) and overweight/obesity (BMI ≥ 25).

Covariates included age, neighborhood SES, education (less than high school, high school graduate or some college, college graduate or above), marital status (married or living with partner vs. other), and employment status (job or unpaid work outside home vs. none).

2.4. Statistical analysis

As 531 cases (5.3% of the 10,008 cases) were missing one or more variables, 100 imputed datasets were created by multiple imputation using chained equations to improve efficiency and reduce possible biases (Little & Rubin, 2014; van Buuren, 2011; Grund et al., 2017). The imputation accounted for the two-stage stratified sampling procedure referred to above, with the predictors comprising the GIS measures, perceived proximity to food outlets, sociodemographic variables and weight status. Our final analysis was based on imputed data sets, and parameter estimates were pooled according to Rubin's rules (Rubin, 1987). Supplementary analyses (not shown) found that results based on complete cases were similar.

Sex-specific BE-weight associations were estimated by generalized additive mixed models (GAMMs) (Wood, 2006). GAMMs are flexible in accommodating different distributional assumptions for the outcomes. We used the Gamma distribution and log-link function for the BMI outcome and the binomial distribution and logit link for overweight/obesity. We further used GAMMs to specify clustering at the administrative-unit level (as random effects), and to assess nonlinear associations with body weight by using thin-plate spline smooth terms for the GIS measures and cubic splines with fixed knots of 3 for the perceived measures (Wood, 2006).

For each weight outcome, we estimated two sets of GAMMs. The first consisted of single environmental variable models (SEV), including each of the seven buffer-specific GIS variables and three perception variables as correlates in separate GAMMs. The second approach was multiple environmental variable models (MEV), including all GIS and perceived environmental variables with a p-value < 0.10 in the sex-specific SEV. As shown in Appendix Table 1, correlations were low to moderate among the BE measures, ranging from -0.43 to 0.45 for the GIS variables and 0.44 to 0.60 for the perceived variables. The MEV models assessed the BE-weight associations independent of all other environmental variables. All SEV and MEV models included fixed effects for city, and the remaining sociodemographic covariates. We present exponentiated regression coefficient (b) and interpret $100–100 \times \exp(b)$ as percent reduction in BMI or the odds of overweight/obesity associated with a 1-unit increase in the examined BE variable. For continuous variables with small effect size, we changed units to report at the fourth decimal of $exp(b)$.

To test the level of heterogeneity in BE-weight associations across the 14 cities, we estimated and compared GAMMs with and without interactions between city and the environmental variables. Model comparison was based on Akaike Information Criterion (AIC) statistic, with models with a lower AIC value by ≥ 2 indicating a better model. AIC provided a global test of interaction effects, avoiding the issue of multiple comparisons (Burnham & Anderson, 2002) arising when making individual two-way comparisons across the 14 cities. The AIC statistic was also used to determine 1) whether there was sufficient evidence of a nonlinear BE-weight association, by comparing GAMMs with nonlinear vs. linear terms, and 2) whether variability in weight was better captured by individual vs. composite BE measures, by comparing the best SEV or MEV models against the best models of composite measures.

To calculate explained variance we used the proportional reduction in variance approach developed by Snijders & Bosker (2011) comparing models with and without the BE attributes. We also estimated the proportion of variance explained by city differences in BMI by fitting models with and without city effects. We conducted sex-specific analyses because preliminary analysis found sex differences in BE-weight associations. All analyses were implemented using R statistical software (R Core Team, 2011), including packages 'mice' (van Buuren & Groothuis-Oudshoorn, 2011), 'mitml' (Grund et al., 2017; Rubin, 1987) and 'mgcv' (van Buuren, 2011).

2.5. Role of funding sources

None of the study funders had any role in the design of the study; conception, analysis, or interpretation of results; writing; or publication submission decisions related to this paper.

3. Results

Table 2 shows descriptive statistics of the continuous and binary weight status variables and sociodemographic covariates. The analytic sample had 10,008 cases (4463 male, ~45%) aged 16 to 66 years with a mean of 42 years. The mean BMI was 26 kg/m^2, 32.0% of the sample were overweight, and 17.2% were obese.

Mean BMI (SD) varied between 22.2 (3.3) kgm^{-2} (Hong Kong) and 28 (5) kgm^{-2} (Cuernavaca). The proportion (95% CI) of the population in the overweight category ranged from 16.6% (13.1, 19.8) (Hong Kong) to 41.1% (37.3, 44.7) (Cuernavaca). Similarly, the proportion of the population in the obesity category ranged from just 2.9% (1.3, 4.4) (Hong Kong) to 31.3% (27.7, 34.7) (Cuernavaca).

Fig. 1 shows age-specific male and female BMI, based on a sex-specific mixed effects model with age and city as covariates. The age patterns of BMI varied substantially across the 14 cities.

Tables 3 and 4 show model estimates for BE association with BMI and overweight/obesity, respectively.

For females, the only GIS measure significantly associated with weight status was distance to public transport stop: every 100 m increase in this distance was associated with a 0.1% (95% CI: 0.0–0.2%) reduction in BMI and a 1.2% (0.1–2.3%) reduction in the odds of overweight/obesity. The significant association with BMI persisted when perceived proximity to other grocery stores was added to the model.

For males, BMI was significantly associated with public transport density in the SEV model: a 1-unit increase in the count of public transport stops per km^2 was associated with a 0.05% (0.00–0.10%) reduction in BMI. This association became non-significant when perceived proximity of food outlets was included in the model. Overweight/obesity was significantly associated with intersection density and public transport density in SEV models: men's odds of overweight/obesity was 1.7% (0.09–2.29%) lower for each 10-unit increase in intersection density and 1.1% (0.48–1.72%) lower for each 1-unit increase in public transport density. The association with transport density persisted in the MEV model that adjusted for intersection density and perceived distance to restaurants.

Table 2
Descriptive statistics of sociodemographic characteristics and body weight, IPEN Adult study.

	All 14 cities	Ghent Belgium	Curitiba Brazil	Bogota Colombia	Olomouc Czech Republic	Aarhus Denmark	Hong Kong	Cuernavaca Mexico	North Shore NZ	Waitakere NZ	Wellington NZ	Christchurch NZ	Stoke-on-Trent, UK	Seattle USA	Baltimore USA
N	10,008	1166	697	963	330	642	477	677	511	512	496	495	843	1287	912
Age	42.0	42.7	41.1	40.0	37.9	38.9	42.4	42.1	41.1	40.8	39.2	41.7	43.0	44.0	46.6
(SD)	(12.7)	(12.6)	(13.2)	(13.7)	(14.7)	(13.9)	(12.7)	(12.6)	(11.8)	(11.8)	(12.6)	(12.6)	(13.3)	(11.0)	(10.7)
NA	66	8	2	0	9	19	1	0	12	1	0	13	0	1	0
(%)	(0.66)	(0.69)	(0.29)	(0.00)	(2.73)	(2.96)	(0.21)	(0.00)	(2.35)	(0.20)	(0.00)	(2.63)	(0.00)	(0.08)	(0.00)
Male	4463	557	328	350	123	270	177	302	184	201	242	219	370	705	435
(%)	(44.6)	(47.8)	(47.1)	(36.3)	(37.3)	(42.1)	(37.1)	(44.6)	(36.0)	(39.3)	(48.8)	(44.2)	(43.9)	(54.8)	(47.7)
NA	23	3	0	0	0	19	0	0	1	0	0	0	0	0	0
(%)	(0.23)	(0.26)	(0.00)	(0.00)	(0.00)	(2.96)	(0.00)	(0.00)	(0.20)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
High SES	5069	587	347	390	196	360	219	340	341	210	248	246	446	660	479
(%)	(50.6)	(50.3)	(49.8)	(40.5)	(59.4)	(56.1)	(45.9)	(50.2)	(66.7)	(41.0)	(50.0)	(49.7)	(52.9)	(51.3)	(52.5)
< HS	1627	51	201	342	63	47	208	293	19	26	4	53	285	17	18
(%)	(16.3)	(4.4)	(28.8)	(35.5)	(19.1)	(7.3)	(43.6)	(43.3)	(3.7)	(5.1)	(0.8)	(10.7)	(33.8)	(1.3)	(2.0)
HS	4047	399	226	407	131	277	108	194	293	328	233	283	436	456	276
(%)	(40.4)	(34.2)	(32.4)	(42.3)	(39.7)	(43.1)	(22.6)	(28.7)	(57.3)	(64.1)	(47.0)	(57.2)	(51.7)	(35.4)	(30.3)
College	4233	701	270	214	92	299	161	186	194	157	259	158	118	811	613
(%)	(42.3)	(60.1)	(38.7)	(22.2)	(27.9)	(46.6)	(33.8)	(27.5)	(38.0)	(30.7)	(52.2)	(31.9)	(14.0)	(63.0)	(67.2)
NA	101	15	0	0	44	19	0	4	5	1	0	1	4	3	5
(%)	(1.01)	(1.3)	(0.0)	(0.0)	(13.3)	(3.0)	(0.0)	(0.6)	(1.0)	(0.2)	(0.0)	(0.2)	(0.5)	(0.2)	(0.5)
Employed	7506	928	541	555	255	479	275	480	397	430	430	394	543	1046	753
(%)	(75.0)	(79.6)	(77.6)	(57.6)	(77.3)	(74.6)	(57.7)	(70.9)	(77.7)	(84.0)	(86.7)	(79.6)	(64.4)	(81.3)	(82.6)
NA	30	0	0	4	0	0	19	6	0	0	0	0	0	1	0
(%)	(0.3)	(0.00)	(0.00)	(0.42)	(0.00)	(0.00)	(3.98)	(0.89)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.08)	(0.00)
Married	6082	849	405	514	163	407	279	438	359	379	280	274	375	812	548
(%)	(60.8)	(72.8)	(58.1)	(53.4)	(49.4)	(63.4)	(58.5)	(64.7)	(70.3)	(74.0)	(56.5)	(55.4)	(44.5)	(63.1)	(60.1)
NA	99	9	0	0	51	20	1	0	1	1	2	0	6	2	6
(%)	(1.0)	(0.8)	(0.0)	(0.0)	(15.5)	(3.1)	(0.2)	(0.0)	(0.2)	(0.2)	(0.4)	(0.0)	(0.7)	(0.2)	(0.7)
BMI	26.0	24.3	26.1	24.7	24.4	24.1	22.2	28.0	26.9	27.4	26.4	27.4	27.6	26.6	27.2
(SD)	(5.2)	(3.9)	(4.5)	(4.1)	(3.8)	(3.7)	(3.4)	(5.0)	(5.7)	(5.6)	(5.1)	(6.1)	(5.6)	(5.5)	(5.7)
Overweight	3203	329	258	285	96	170	79	278	163	184	191	156	224	435	355
(%)	(32.0)	(28.2)	(37.0)	(29.6)	(29.1)	(26.5)	(16.6)	(41.1)	(31.9)	(35.9)	(38.5)	(31.5)	(26.6)	(33.8)	(38.9)
Obesity	1724	96	128	102	29	40	14	212	119	127	82	129	182	262	202
(%)	(17.2)	(8.2)	(18.4)	(10.6)	(8.8)	(6.2)	(2.9)	(31.3)	(23.3)	(24.8)	(16.5)	(26.1)	(21.6)	(20.4)	(22.1)
NA	300	38	2	0	0	19	6	0	7	11	2	6	196	3	10
(%)	(3.0)	(3.3)	(0.3)	(0.0)	(0.0)	(3.0)	(1.3)	(0.0)	(1.4)	(2.1)	(0.4)	(1.2)	(23.3)	(0.2)	(1.1)

Notes: Mean or frequency; N sample size; SD standard deviation; NA not available (missing data); SES socioeconomic status; HS high school; BMI body mass index; Overweight defined as BMI 25 to < 30; Obesity defined as BMI 30 and greater.

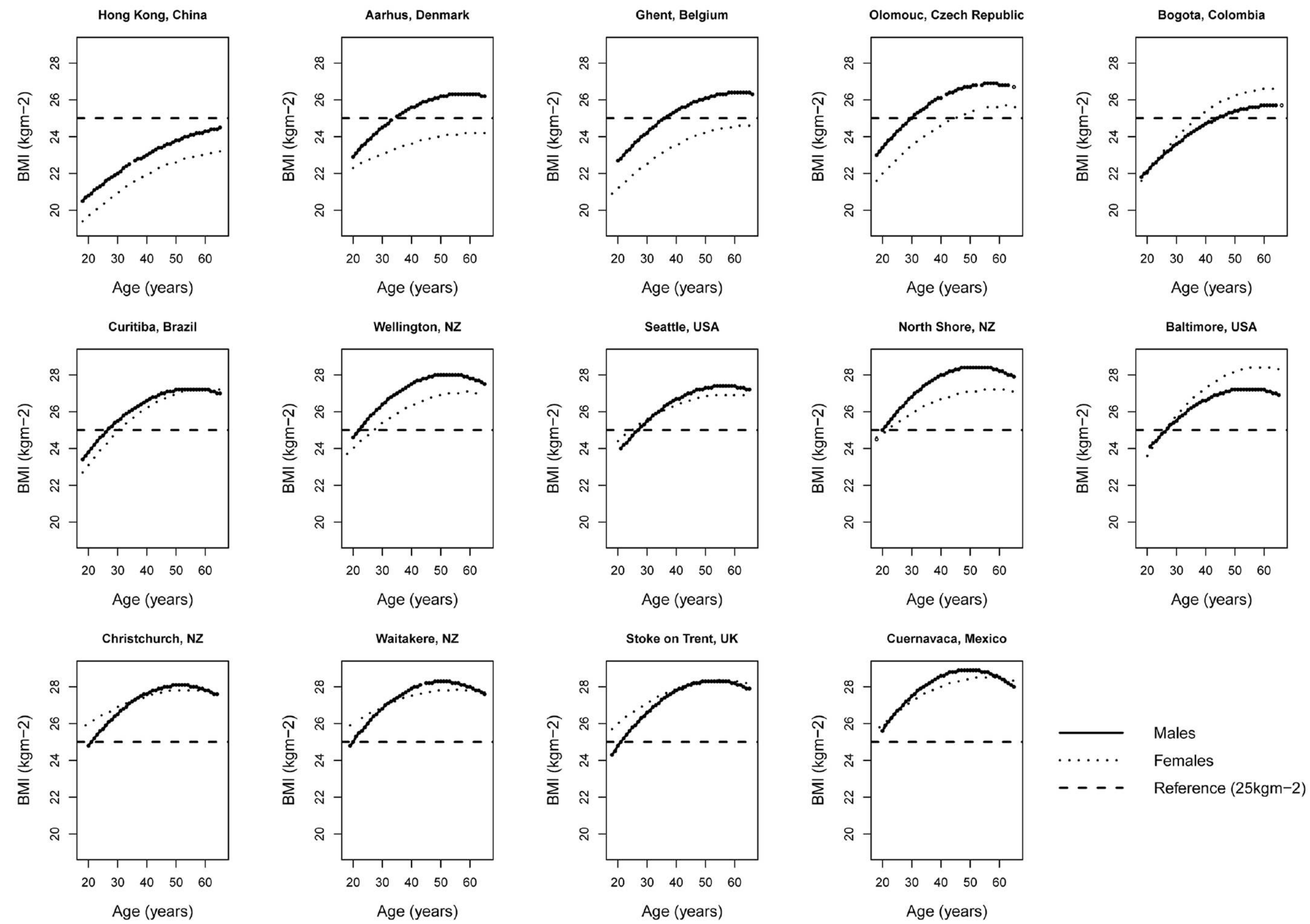

Fig. 1. Age-specific mean body mass index (BMI) by sex across the 14 cities. Plots are sorted by overall mean BMI – lowest, top left to highest, bottom right.

Regarding proximity of food outlets, in the MEV model for females, BMI was 0.68% (0.04–1.32%) lower when perceived walking time to grocery stores other than supermarkets decreased by one category (e.g. changed from > 30 to 20–30 min). For males, BMI and the odds of overweight/obesity in SEV models were significantly lower by 0.49% (0.02–0.97%) and 8.35% (2.41–14.27%), respectively, when walking time to restaurants decreased by one category. However, neither association was significant when public transport density was included in MEV models.

For both sexes, we found no sufficient evidence of nonlinear associations or city heterogeneities in BE-weight associations. Thus, the same associations of lower overweight/obesity with greater public transport density (for men) and of lower BMI with greater distance to nearest public transport (for women) held across the wide spectrum of BE in the 14 cities.

The explained variance in BMI for individual objective neighborhood measures in the pooled analysis was small, 0.1% for the female SEV model with distance to public transport, and 0.08% for the male SEV model with public transport density. In contrast, the explained variance for city was much greater at 11.3% for females and 9.2% for males.

3.1. Composite built environment variables

Table 5 shows body weight status associations with composite BE measures. For females, one standard deviation increase in the composite of residential density, intersection density, land use mix and distance to public transport was associated with a reduction of 0.39% (0.02–0.76%) in BMI and a reduction of 5.27% (0.42–10.12%) in the odds of overweight/obesity. For males, overweight/obesity was significantly associated with the composite of residential density, intersection density, land use mix, public transport density and number of parks contained in the buffer, the composite of perceived proximity to all three types of food outlets, and the composite of the preceding BE attributes combined. Men's odds of overweight/obesity was lower by 3.95% (1.11–6.79%), 3.09% (0.23–5.94%) and 2.48% (0.79–4.17%) for one standard deviation increase in the three composite measures, respectively. Men's BMI was lower by 0.23% (0.01–0.45%) and 0.13% (0.00–0.27%), respectively, for one standard deviation increase in perceived proximity to food outlets and in the combined composite.

For males, the BMI and overweight/obesity models of composites combining GIS and perception measures were better than MEV models. For females, results depended on the outcome. The composites model was worse than the MEV model for BMI but had a smaller AIC that was within 2 units of the AIC of the best SEV model for overweight/obesity, indicating the composites model was as good as the SEV model for the latter outcome. Note that as shown in Table 4, no MEV model was estimated for female overweight/obesity because except for distance to public transport, no single BE measure was significantly associated with overweight/obesity among women.

4. Discussion

Of seven GIS-based and three perceived BE variables, lower body weight status was significantly associated with greater distance to public transport among females, and greater road network intersection

Table 3
Estimates for associations of body mass index with objective and perceived measures of built environment attributes, IPEN Adult study.

Built environment attributes	Single Environmental variable		Multiple environmental variables	
	exp(b)	95% CI	exp(b)	95% CI
Female				
Objective GIS-based				
Network residential density (1000 dwellings per km^2)	0.9996	0.9988–1.0004	–	–
Network intersection density (10 intersections per km^2)	0.9995	0.9981–1.0009	–	–
Land use mix	0.9939	0.9670–1.0208	–	–
Ratio of Retail and civic to total buffer area	1.0133	0.9856–1.0409	–	–
Public transport density (per km^2)	1.0003	0.9997–1.0009	–	–
Distance to nearest public transport stop (10 m)	0.9999	0.9998–1.0000	0.9999	0.9998–1.0000
Parks contained by buffer (per km^2)	1.0008	0.9998–1.0018	–	–
Perceived proximity of food outlets				
Supermarkets	0.9989	0.9942–1.0037	–	–
Other grocery stores	0.9944	0.9880–1.0007	0.9932	0.9868–0.9996
Restaurants (any type)	0.9985	0.9934–1.0037	–	–
Male				
Objective GIS-based				
Network residential density (1000 dwellings per km^2)	0.9998	0.9991–1.0005	–	–
Network intersection density (10 intersections per km^2)	0.9993	0.9980–1.0005	–	–
Land use mix	0.9998	0.9774–1.0222	–	–
Ratio of Retail and civic to total buffer area	1.0119	0.9868–1.0370	–	–
Public transport density (per km^2)	0.9995	0.9990–1.0000	0.9996	0.9991–1.0001
Distance to nearest public transport stop (10 m)	1.0000	0.9999–1.0001	–	–
Parks contained by buffer (per km^2)	0.9999	0.9990–1.0009	–	–
Perceived proximity of food outlets				
Supermarkets	0.9963	0.9920–1.0007	0.9965	0.9911–1.0020
Other grocery stores	0.9953	0.9893–1.0013	–	–
Restaurants (any type)	0.9951	0.9903–0.9998	0.9987	0.9938–1.0037

All models adjusted for fixed effects of city, age and squared age, socioeconomic status, educational attainment, marital status and employment status, and random effects of survey administrative units; models with multiple environmental variables include variables with *p*-value $< .1$ in models with single environmental variables; 1 km buffer for all objective GIS (geographic information system) measures; exp(b) exponentiated regression coefficient estimate; CI confidence interval.

Table 4
Estimates for associations of overweight/obesity status with objective and perceived measures of built environment attributes, IPEN Adult study.

Built environment attributes	Single environmental variable		Multiple environmental variables	
	exp(b)	95% CI	exp(b)	95% CI
Female				
Objective GIS-based				
Network residential density (1000 dwellings per km^2)	1.0004	0.9910–1.0097	–	–
Network intersection density (10 intersections per km^2)	0.9932	0.9782–1.0083	–	–
Land use mix	0.9609	0.6794–1.2424	–	–
Ratio of Retail and civic to total buffer area	1.1147	0.7819–1.4475	–	–
Public transport density (per km^2)	1.0026	0.9958–1.0094	–	–
Distance to nearest public transport stop (10 m)	0.9988	0.9977–0.9999	–	–
Parks contained by buffer (per km^2)	1.0055	0.9944–1.0166	–	–
Perceived proximity of food outlets				
Supermarkets	0.9985	0.9461–1.0509	–	–
Other grocery stores	0.9665	0.8978–1.0353	–	–
Restaurants (any type)	0.9913	0.9337–1.0489	–	–
Male				
Objective GIS-based				
Network residential density (1000 dwellings per km^2)	0.9971	0.9871–1.0072	–	–
Network intersection density (10 intersections per km^2)	0.9831	0.9671–0.9991	0.9932	0.9762–1.0101
Land use mix	0.8041	0.5673–1.0409	–	–
Ratio of Retail and civic to total buffer area	1.0805	0.7085–1.4525	–	–
Public transport density (per km^2)	0.9889	0.9827–0.9952	0.9911	0.9844–0.9978
Distance to nearest public transport stop (10 m)	1.0007	0.9996–1.0018	–	–
Parks contained by buffer (per km^2)	0.9963	0.9836–1.0091	–	–
Perceived proximity of food outlets				
Supermarkets	0.9679	0.9110–1.0248	–	–
Other grocery stores	0.9413	0.8645–1.0180	–	–
Restaurants (any type)	0.9165	0.8572–0.9759	0.9404	0.8771–1.0038

Overweight/obesity defined as body mass index 25 and greater; all models adjusted for fixed effects of city, age and squared age, socioeconomic status, educational attainment, marital status and employment status, and random effects of survey administrative units; models with multiple environmental variables include variables with p-value $< .1$ in models with single environmental variables; 1 km buffer for all objective GIS (geographic information system) measures; exp(b) exponentiated regression coefficient estimate; CI confidence interval.

Table 5
Estimates for associations of body mass index (BMI) and overweight/obesity with composite measures of built environment attributes, IPEN Adult study.

Composite measures	BMI		Overweight/obesity (BMI 25 and greater)	
	exp(b)	95% CI	exp(b)	95% CI
Female				
GIS-based				
(1) Residential density, intersection density, land use mix, distance to public transport	0.9961	0.9924–0.9998	0.9473	0.8988–0.9958
(2) Ratio of retail and civic land to total buffer area, public transport density, parks contained in buffer	1.0032	0.9993–1.0071	1.0166	0.9732–1.0600
Perceived proximity				
(3) Supermarkets, other grocery stores, restaurants	0.9987	0.9963–1.0011	0.9936	0.9672–1.0200
(1) and (3) combined	0.9984	0.9966–1.0002	0.9860	0.9645–1.0076
Male				
GIS-based				
(1) Residential density, intersection density, land use mix, public transport density, parks contained buffer	0.9985	0.9963–1.0008	0.9605	0.9321–0.9889
(2) Ratio of retail and civic land to total buffer area, distance to public transport	1.0026	0.9982–1.0069	1.0533	0.9908–1.1158
Perceived proximity				
(3) Supermarkets, other grocery stores, restaurants	0.9977	0.9955–0.9999	0.9691	0.9406–0.9977
(1) and (3) combined	0.9987	0.9973–1.0000	0.9752	0.9583–0.9921

All models adjusted for fixed effects of city, age and squared age, socioeconomic status, educational attainment, marital status and employment status, and random effects of survey administrative units; composites were constructed by summed z-scores of single measures that were associated with weight outcomes in the same direction; for females, residential density was negatively associated with BMI and positively associated with overweight/obesity, and included in Composite (1) in the table; for weight associations with individual built environment attributes, see Tables 3 and 4; for all objective measures: 1 km buffer used for GIS (geographic information system) measures, except for female BMI, where 500 m buffer was used; exp(b) exponentiated regression coefficient estimate; CI confidence interval.

density, public transport stop density and perceived proximity to restaurants among males. One composite of GIS measures was associated with women's weight status, and three composite measures (GIS, perception and the two combined) were associated with men's weight status. Effect sizes for composite measures were stronger than effect sizes for single BE variables among men but not women.

These results provide some support for a conclusion that changing combinations of, rather than single, environmental attributes may be more effective as obesity control strategies. This conclusion is conceptually similar to a US Guide to Community Preventive Services (Community Preventive Services Task Force, 2016) recommendation that combinations of built environment changes are effective interventions for physical activity. One standard deviation improvement in the composite measures of BE was associated with reductions of 0.1–0.5% in BMI and reductions of 2.5–5.3% in the odds of overweight/obesity. To put this in perspective, these effect size estimates were similar to, or larger than, global annual increases in weight status over the last 40 years. Worldwide, BMI increased at an annual rate of about 0.3% between 1975 and 2014 (NCD Risk Factor Collaboration, 2016), and the odds of overweight/obesity increased by about 1.3% per annum between 1980 and 2013 (Ng et al., 2014). Although it is not feasible to extrapolate from cross-sectional observations to longitudinal changes, present findings are supportive of a meaningful role for the built environment in reducing population levels, contributing to partial mitigation of annual increases in overweight and obesity. Because built environment changes are relatively permanent, such interventions could be expected to have sustainable impactS on population obesity control.

For females, being further from a public transport stop or nearer to food outlets other than supermarkets or restaurants was related to lower body weight. Though the public transit result was unexpected, a possible explanation is for women using public transport regularly, the greater the distance walked to the transport stop, the greater the expected energy expenditure. On the other hand, the shorter the perceived walking time to a grocery store, the more likely a woman may be to regularly walk and potentially lower BMI through greater energy expenditure and better access to a variety of foods. In MEV models for males, greater public transport *density* was inversely related to overweight/obesity, suggesting that more public transport *options* may facilitate more use of this active travel mode among men. It was notable that the proximity (related to access) to public transport had a different relation to weight status than did density (related to options) of public transport stops. Public transport use contributes to more total physical activity (Community Preventive Services Task Force, 2016), so public transport deserves more attention as a public health intervention. The sex-specific findings should be followed up with more detailed measures of transit-related variables such as type of transit, access/proximity, frequency of service, and quality of stops/stations. Though it would be helpful to explore sex—and age–differences in perceptions or use of public transit, such findings may present practical challenges to transit managers to optimize design for both sexes and all ages. Among males, lower perceived walking time to the nearest restaurant and higher network intersection density were significantly related to less risk of overweight/obesity. Higher intersection density provides direct routes to destinations and has been associated with more transport walking (Ding & Gebel, 2012), and more proximal restaurants could facilitate men walking for restaurant meals more often.

The ‘city’ variable explained more variation in mean BMI and overweight/obesity than BE variables. City variation is illustrated in Fig. 1, where, for example, in Hong Kong the mean BMI never reaches the overweight threshold at any of the age groups, whereas for Cuernavaca BMI was above the threshold for all age groups. There are likely many aspects of built, social, and cultural environments in cities relevant to weight status beyond the BE variables assessed in the present study.

The difference in mean BMI between females and males within cities is another important observation. Six cities (Hong Kong, Aarhus, Ghent, Olomouc, Wellington and North Shore) showed a pattern where females had consistently lower mean BMI throughout the age range, six cities (Curitiba, Seattle, Christchurch, Waitakere, Stoke on Trent and Cuernavaca) had broadly similar patterns, and two cities (Bogota and Baltimore) had a pattern with progressively greater mean BMI with age for females. Future research is recommended to explore factors that explain these city-specific differences between the sexes.

Present findings reinforce recommendations for a mix of societal and environmental changes to reduce overweight/obesity worldwide (Swinburn et al., 2011; Centers for Disease Control and Prevention, 2005; WHO, 2013; Roberto et al., 2015). The mix of interventions may need to vary across cities or countries and between sexes. Because built environments are driven by government and corporate policies

(Swinburn, 2008; Giles-Corti et al., 2016), international policy studies are needed to enhance understanding of multi-level influences on obesity. Based on significant findings with both food and physical activity environments, it would seem prudent to focus attention on intervention strategies to influence the supply and demand for healthful food alongside changes to the built environment.

Associations of weight status with the BE measures were linear and generalizable across a wide range of neighborhood characteristics and cultures. The key features of urban design that emerged from this analysis were those that encourage active transport through moderate distances to public transport stops (for women) and more transport stops within walking distance (for men), well-connected streets to provide direct paths to destinations, and food outlets within walking distance. More proximal food outlets, however, would need to be tempered by efforts to control the supply of and/or demand for low-nutrition food.

Some limitations of the study should be noted. First, weight and height were not gathered objectively in all countries. The greater error in reported weight and height effectively reduced power to detect effects, though this was mitigated by the large sample size. Second, although ethnic or cultural variation was undoubtedly present in the sample, it was not feasible to account for this variation in the models because there was no direct measure of "culture." However, if cultural variation was a major influence, then we would have expected numerous interactions between perceived food environments and city. Because few significant interactions were found, it appears built environments operate somewhat independently of culture-based perceptions. Third, SES was measured differently across cities, which we expect added some error to analyses and reduced observed associations. Fourth, only a single cut-point for overweight/obesity was applied to all participants instead of using ethnicity-specific cut-points. Fifth, the food environment variables were simple and did not address other aspects of the food environment such as healthfulness of foods offered, price, promotion, density of food outlets, or frequency of visits.

Future studies should include longitudinal designs, including participants who change neighborhoods, to improve ability to make causal interpretations. More data on individual behaviors, preferences, and assets (e.g. car ownership), as opposed to just demographic and neighborhood characteristics, should be gathered to allow a more complete understanding of multiple levels of influence on overweight/obesity. We encourage investigators to include measures of culture in future studies, which could help account for the variance accounted for by "city". Aspects of culture of particular relevance to weight outcomes may be norms and beliefs related to eating, physical activity, and transportation behaviors. Given the strength of public transport variables in the present study, more research on type of transport, quality of service, and segmentation by automobile access could point to additional strategies for obesity control. As policy options evolve into actions, it would be valuable to evaluate the effects of environmental changes and multilevel interventions through natural experiments with common measures across countries.

5. Conclusions

In pooled analyses across 14 cities in 10 countries, environmental correlates of weight status differed for women and men. For women, correlates of healthier weight status were greater distance to public transport stops and shorter distance to grocery stores other than supermarkets. For men, public transport density, road intersection density, and proximity to restaurants were related to healthier weight status. Composite measures of the built environment had stronger effect sizes than single variables for men but not women. For composite measures, associations with BMI were small, and associations with overweight/obesity were modest but meaningful. Based on present results, strategies to expand neighborhood environments that support public transport and have sources of food readily accessible by active transport hold promise for making modest contributions to global obesity control. The variation in weight status attributable to "cities" was larger than expected, suggesting the importance of examining a wider range of physical activity, food, and cultural environment variables in future international studies.

Author contributions

All authors read, revised, and approved the submitted manuscript.

Thomas Cochrane conceived the manuscript, developed the analytic plan, drafted introduction, discussion and conclusion sections.

Yan Yu conceived the manuscript, developed the analytic plan, performed the analyses, drafted the analysis methods and results sections,

Rachel Davey conceived the manuscript, drafted introduction, discussion and conclusion sections, participated in the country-level coordination, recruitment, and study implementation.

Ester Cerin oversaw the analyses, participated in the country-level coordination, recruitment, and study implementation.

Kelli Cain led the coordinating centre activities, participated in the country-level coordination, recruitment, and study implementation.

Terry Conway managed the pooled database, was on the coordinating centre team, participated in the country-level coordination, recruitment, and study implementation.

Jacqueline Kerr was on the coordinating centre team, participated in the country-level coordination, recruitment, and study implementation.

Lawrence Frank was on the coordinating centre team, contributed to all GIS work, participated in the country-level coordination, recruitment, and study implementation.

James Chapman was on the coordinating centre team, contributed to all GIS work, participated in the country-level coordination, recruitment, and study implementation.

Marc Adams was on the coordinating centre team, led development of GIS templates, contributed to all GIS work, participated in the country-level coordination, recruitment, and study implementation.

Duncan Macfarlane participated in the country-level coordination, recruitment, and study implementation

Delfien Van Dyck participated in the country-level coordination, recruitment, and study implementation.

Poh-Chin Lai participated in the country-level coordination, recruitment, and study implementation.

Olga Sarmiento participated in the country-level coordination, recruitment, and study implementation

Josef Mitáš participated in the country-level coordination, recruitment, and study implementation

Grant Schofield participated in the country-level coordination, recruitment, and study implementation

Deborah Salvo participated in the country-level coordination, recruitment, and study implementation

Rodrigo Reis participated in the country-level coordination, recruitment, and study implementation

Jens Troelsen participated in the country-level coordination, recruitment, and study implementation

Neville Owen contributed to development of the IPEN Adult study, participated in the country-level coordination, recruitment, and study implementation.

James F. Sallis conceived of the IPEN Adult study, led the coordinating centre, participated in the country-level coordination, recruitment, and study implementation.

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Ethical approval

All investigators received approval under their country's ethical requirements, and all participants provided informed consent. The pooled data study met the NIH Fogarty International Center ethical requirements.

Declaration of competing interest

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Appendix A

Table 1
Pearson correlations among built environment variables in the IPEN Adult study.

Built environmental measures	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) Residential density per km^2	1.00									
(2) Intersection density per km^2	0.33	1.00								
(3) Land use mix	0.45	0.22	1.00							
(4) Ratio of retail and civic land area to total buffer area	0.36	0.06	0.60	1.00						
(5) Public transport density per km2	0.00	0.01	0.06	0.03	1.00					
(6) Street network distance (m) to nearest transport stop or station	−0.01	0.34	−0.13	−0.12	−0.43	1.00				
(7) Number of parks contained or intersected by buffer of 0.5 km	0.19	0.44	0.14	0.00	−0.17	0.37	1.00			
(8) Perceived proximity to supermarkets	0.26	0.29	0.39	0.22	0.06	0.01	0.25	1.00		
(9) Perceived proximity to other grocery stores	0.15	0.31	0.26	0.12	0.17	−0.07	0.18	0.44	1.00	
(10) Perceived proximity to restaurants	0.16	0.28	0.29	0.17	0.16	−0.04	0.23	0.50	0.60	1.00

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