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Article *in* The Lancet · April 2016

DOI: 10.1016/S0140-6736(15)01284-2

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Physical activity in relation to urban environments in 14 cities worldwide: a cross-sectional study

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Summary

Background Physical inactivity is a global pandemic responsible for over 5 million deaths annually through its effects on multiple non-communicable diseases. We aimed to document how objectively measured attributes of the urban environment are related to objectively measured physical activity, in an international sample of adults.

Methods We based our analyses on the International Physical activity and Environment Network (IPEN) adult study, which was a coordinated, international, cross-sectional study. Participants were sampled from neighbourhoods with varied levels of walkability and socioeconomic status. The present analyses of data from the IPEN adult study included 6822 adults aged 18–66 years from 14 cities in ten countries on five continents. Indicators of walkability, public transport access, and park access were assessed in 1·0 km and 0·5 km street network buffers around each participant's residential address with geographic information systems. Mean daily minutes of moderate-to-vigorous-intensity physical activity were measured with 4–7 days of accelerometer monitoring. Associations between environmental attributes and physical activity were estimated using generalised additive mixed models with gamma variance and logarithmic link functions.

Results Four of six environmental attributes were significantly, positively, and linearly related to physical activity in the single variable models: net residential density (exp[b] 1·006 [95% CI 1·003–1·009]; p=0·001), intersection density (1·069 [1·011–1·130]; p=0·019), public transport density (1·037 [1·018–1·056]; p=0·0007), and number of parks (1·146 [1·033–1·272]; p=0·010). Mixed land use and distance to nearest public transport point were not related to physical activity. The difference in physical activity between participants living in the most and least activity-friendly neighbourhoods ranged from 68 min/week to 89 min/week, which represents 45–59% of the 150 min/week recommended by guidelines.

Interpretation Design of urban environments has the potential to contribute substantially to physical activity. Similarity of findings across cities suggests the promise of engaging urban planning, transportation, and parks sectors in efforts to reduce the health burden of the global physical inactivity pandemic.

Funding Funding for coordination of the IPEN adult study, including the present analysis, was provided by the National Cancer Institute of National Institutes of Health (CA127296) with studies in each country funded by different sources.

Published Online
April 1, 2016
http://dx.doi.org/10.1016/S0140-6736(15)01284-2

See Online/Comment
http://dx.doi.org/10.1016/S0140-6736(16)00348-2

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Introduction

Physical inactivity is a global pandemic, responsible for more than 5 million deaths per year and is one of the UN's primary targets to reduce non-communicable diseases.[1–3] Improvements to urban environments to facilitate physical activity for transportation and recreation is a recommended strategy.[4,5]

People who live in walkable neighbourhoods that are densely populated, have interconnected streets, and are close to shops, services, restaurants, public transport, and parks, tend to be more physically active than residents of less walkable areas.[6,7] Studies of built environments and physical activity have been criticised for being done in only a few countries,[6,8,9] not capturing all types of urban environment, and relying on self-reported environmental measures. International studies are needed to represent the full range of environmental variability. If findings are generally applicable across countries, then built environment interventions are likely to be viewed as relevant to non-communicable disease policies internationally.

The purpose of this 14 city and ten country study was to document the strength, shape, and generalisability of associations between neighbourhood environment attributes and total moderate to vigorous intensity physical activity (MVPA). Objective measures of built environments and physical activity enhance precision and credibility of the findings.

Methods

Study design and neighbourhood selection

The International Physical Activity and Environment Network (IPEN) adult study was a multicountry cross-sectional epidemiological study with the same design and similar methods, described in detail elsewhere.[10] The study included participants from 17 cities in 12 countries: Australia (Adelaide), Belgium (Ghent), Brazil (Curitiba), Colombia (Bogota), Czech Republic (Olomouc and

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Research in context

Evidence before this study

Evidence is growing that the design of urban environments has a role in the pandemic of physical inactivity, which is contributing to several non-communicable diseases. Numerous reviews have reported evidence that adults tend to be more physically active when they live in higher density, mixed-use neighbourhoods with destinations such as shops and parks within walking distance. However, findings have been inconsistent, perhaps due in part to assessments of only individual geographical sites with little environmental variability, infrequent use of standardised measures, and over-reliance on self-reported measures. Improvements in the evidence about built environments and physical activity are important because environments are constantly changing in ways that could have positive or negative effects on whole populations over many years.

Added value of this study

This analysis of data from a coordinated international study was designed to improve the quality of evidence by assessing a broad range of built environments across 14 cities in ten middle-income and high-income countries on five continents. The quality of measures was enhanced by using comparable objective measures of built environments (geographic information systems) and physical activity (electronic accelerometers that recorded motion every minute). Four of six environmental attributes were significantly, positively, independently, and linearly related to physical activity in the single variable models: residential density, intersection density, number of public transport stops, and number of parks within walking distance. The study provided novel information about the important role of access to public transport. In models adjusting for all the significant built environment variables, adults who lived in the most activity-friendly neighbourhoods did 68–89 min more of physical activity per week than those in the least activity-friendly neighbourhoods. This difference is larger than reported in most other studies. The relation of built environments to physical activity was generally similar across diverse cities, suggesting changing built environments is a solution that could be applied internationally.

Implications of all the available evidence

This study adds strength to previous calls for policy changes in the urban planning, transport, and parks and recreation sectors. Communities with high residential density also tend to have connected streets, shops, and services within walking distance. Access to public transport encourages physical activity because people walk to and from buses and trains. Public parks provide places for recreational physical activity. These activity-friendly characteristics can be deemed to be design principles that apply across countries. Because the associations were linear, every environmental improvement can be expected to contribute to increased physical activity, irrespective of whether the residents of the city are starting at a low or high level. The large differences in physical activity between participants living in the most and least activity-friendly neighbourhoods provide strong justification for public health agencies to work with other agencies to create healthier cities. Making cities more activity-friendly than at present could be a partial but substantial long-term solution to international pandemics of physical inactivity and non-communicable diseases.

Hradec Kralove), Denmark (Aarhus), China (Hong Kong), Mexico (Cuernavaca), New Zealand (North Shore, Waitakere, Wellington, and Christchurch), Spain (Pamplona), the UK (Stoke-on-Trent), and the USA (Seattle, WA; and Washington, DC and Baltimore, MD). The IPEN adult study was designed to maximise variation in neighbourhood walkability and socioeconomic status (SES) by identifying similar numbers of neighbourhoods stratified as having higher walkability and higher SES,[11] higher walkability and lower SES, lower walkability and higher SES, and lower walkability and lower SES. Neighbourhood walkability index scores were created for small geographical areas in each city (termed administrative units, equivalent to US Census block groups) with geographic information systems (GIS),[11] with some differences by country.[10] Net residential density, intersection density, and mixed land use variables were standardised, and the mean of the three *z* scores was computed as the index.[11] The SES indicator was usually area-level income, but sometimes it was education or a government-created composite.[10] Indicators were chosen based on the data available. Neighbourhoods that met the criteria for the four stratification groups were selected and participants were recruited from those neighbourhoods.

Participant recruitment

Households in selected neighbourhoods were identified with databases from commercial and government sources with various methods used to obtain representative samples in each neighbourhood, including recruitment by mail or telephone and personal visits.[10] In each selected household an adult was invited to complete a survey and wear an accelerometer to objectively measure physical activity. Study dates ranged from 2002 to 2011 across countries, with each country typically recruiting over a full year. Each country obtained ethics approval from their local institutional review boards and all participants provided written informed consent.

Participants

The IPEN adult study included 14 222 adults aged 18–66 years. The present study included 10 008 participants also aged 18–66 years from 14 of the 17 cities from

 www.thelancet.com Published online April 1, 2016 http://dx.doi.org/10.1016/S0140-6736(15)01284-2

ten countries where objective measures were available. Three cities were excluded because either no accelerometer data were collected (Adelaide, Australia) or no GIS data were available (Pamplona, Spain, and Hradec Kralove, Czech Republic). About a quarter (n=2739) of participants did not wear an accelerometer, either because they did not consent or the investigators could not afford to collect accelerometer data for all participants. For cities able to collect accelerometer data for all participants, 87–100% provided complete data. Characteristics of the 6822 participants with 4 or more days of valid accelerometer data by city are shown in table 1. Of these participants, 1740 (26%) were in the higher walkability and higher SES quadrant, 1736 (25%) were in the higher walkability and lower SES quadrant, 1845 (27%) were in the lower walkability and higher SES quandrant, and 1501 (22%) were in the lower walkability and lower SES quadrant.

Outcomes

Physical activity was measured objectively with accelerometers, a reliable, valid, and accepted method.[12–14] Participants were instructed to wear accelerometers for 7 days around the waist, except during sleep, swimming, and showering. Except for New Zealand, which used Actical devices (Philips Respironics, Murrysville, PA, USA), all countries used varying models of ActiGraph monitors (Pensacola, FL, USA). Only vertical axis data were included in the scoring, expressed as counts per min (cpm). For Actical data, we developed moderate (730–3399 cpm) and vigorous (≥3400 cpm) intensity cutpoints to enable comparison with the ActiGraph estimates.[15] 60 s periods were used in data collection and non-wear time was defined as 60 consecutive min or more with zero cpm. Valid days had 10 h or more of wear time. Participants with 4 or more valid days were included in analyses. These methods were consistent with recommendations and common practices.[12,16] Data were scored with MeterPlus 4.3 software, with Freedson's cutpoint of 1952 cpm for moderate intensity to derive the outcome variable, mean minutes of MVPA per valid day.[17]

Variables related to built environment were created with GIS software. Areas known as buffers within 0·5 km and 1·0 km of the participants' homes, reachable by the street network, were defined to estimate accessible neighbourhood features. Templates were developed to guide international teams on constructing comparable GIS variables.[18] The templates were also used to document protocol adherence, which allowed for comparability evaluations. A description of GIS methods and variables, examples of data sources for each country, comparability evaluations, and descriptive results of variation in GIS-based environmental variables within and across cities has been published.[18] The following variables were adequately comparable across cities and were used in analyses: net residential density, street intersection density, retail and civic land use ratio to buffer area (access to common destinations), public

For **MeterPlus 4.3 software** see http://www.meterplussoftware.com

	All cities	Ghent, Belgium*	Curitiba, Brazil†	Bogota, Colombia†	Olomouc, Czech Republic*	Aarhus, Denmark†	Hong Kong, China†	Cuernavaca, Mexico*	North Shore, New Zealand*	Waitakere, New Zealand*	Wellington, New Zealand*	Christchurch, New Zealand*	Stoke-on-Trent, UK†	Seattle, WA, USA*	Baltimore, MD, USA*
Sociodemographic characteristics															
Number with ≥4 days valid physical activity data	6822 (68%)	1050 (90%)	330 (47%)	223 (23%)	258 (78%)	272 (42%)	269 (56%)	656 (97%)	373 (73%)	399 (78%)	416 (84%)	373 (75%)	135 (16%)	1198 (93%)	870 (95%)
Age (years)	43 (12)	43 (13)	42 (13)	46 (12)	39 (14)	40 (14)	42 (13)	42 (13)	43 (12)	42 (11)	40 (12)	43 (12)	44 (13)	44 (11)	47 (11)
Male sex	3161 (46·3%)	508 (48·4%)	160 (48·5%)	71 (31·8%)	93 (36·0%)	106 (39·0%)	109 (40·5%)	300 (45·7%)	139 (37·3%)	161 (40·4%)	198 (47·6%)	170 (45·6%)	63 (46·7%)	659 (55·0%)	424 (48·7%)
Education level															
Less than high school	837 (12·3%)	45 (4·3%)	92 (27·9%)	104 (46·6%)	53 (20·5%)	20 (7·4%)	98 (36·4%)	286 (43·6%)	9 (2·4%)	15 (3·8%)	2 (0·5%)	32 (8·6%)	52 (38·5%)	13 (1·1%)	16 (1·8%)
High school graduate	2597 (38·1%)	340 (32·4%)	103 (31·2%)	81 (36·3%)	100 (38·8%)	115 (42·3%)	62 (23·0%)	188 (28·7%)	215 (57·6%)	258 (64·7%)	187 (45·0%)	212 (56·8%)	62 (45·9%)	417 (34·8%)	257 (29·5%)
College or more	3335 (48·9%)	654 (62·3%)	135 (40·9%)	38 (17·0%)	77 (29·8%)	137 (50·4%)	109 (40·5%)	178 (27·1%)	145 (38·9%)	126 (31·6%)	227 (54·6%)	128 (34·3%)	20 (14·8%)	766 (63·9%)	595 (68·4%)
Missing data	53 (0·8%)	11 (0·1%)	0 (0·0%)	0 (0·0%)	28 (10·9%)	0 (0·0%)	0 (0·0%)	4 (0·6%)	4 (1·1%)	0 (0·0%)	0 (0·0%)	1 (0·3%)	1 (0·7%)	2 (0·2%)	2 (0·2%)

(Table 1 continues on next page)

	All cities	Ghent, Belgium*	Curitiba, Brazil†	Bogota, Colombia†	Olomouc, Czech Republic*	Aarhus, Denmark†	Hong Kong, China†	Cuernavaca, Mexico*	North Shore, New Zealand*	Waitakere, New Zealand*	Wellington, New Zealand*	Christchurch, New Zealand*	Stoke-on-Trent, UK†	Seattle, WA, USA*	Baltimore, MD, USA*
(Continued from previous page)															
Employed	5370 (78·7%)	843 (80·3%)	262 (79·4%)	135 (60·5%)	201 (77·9%)	205 (75·4%)	163 (60·6%)	466 (71·0%)	285 (76·4%)	344 (86·2%)	364 (87·5%)	319 (85·5%)	87 (64·4%)	974 (81·3%)	722 (83·0%)
Married or living with partner	4389 (64·3%)	766 (73·0%)	199 (60·3%)	137 (61·4%)	155 (60·1%)	188 (69·1%)	151 (56·1%)	425 (64·8%)	265 (71·0%)	303 (75·9%)	249 (59·9%)	213 (57·1%)	61 (45·2%)	768 (64·1%)	529 (60·8%)
Accelerometer variables															
Valid days of accelerometer wear time	6·5 (1·1)	6·7 (1·1)	6·7 (1·0)	6·6 (1·0)	6·2 (1·2)	7·0 (0·8)	5·9 (1·0)	5·7 (1·0)	6·4 (1·3)	6·4 (1·3)	6·7 (1·3)	6·5 (1·3)	6·6 (1·0)	6·7 (0·8)	6·7 (1·2)
Accelerometer wear time (h/day)	14·4 (1·3)	14·7 (1·3)	14·0 (1·3)	13·9 (1·2)	13·9 (1·4)	14·9 (1·1)	14·4 (1·4)	14·0 (1·4)	14·2 (1·2)	14·1 (1·3)	14·0 (1·2)	14·0 (1·2)	14·6 (1·2)	14·7 (1·3)	14·8 (1·4)
MVPA (min/day)‡	37·3 (26·5)	35·5 (23·5)	31·5 (24·6)	37·0 (26·4)	47·1 (27·7)	39·7 (23·2)	44·9 (25·3)	31·2 (25·2)	45·7 (28·4)	37·2 (29·2)	50·1 (31·0)	44·0 (32·5)	36·7 (27·3)	36·3 (24·9)	29·2 (22·0)

Data are mean (SD) or n (%) unless otherwise indicated. Totals might not be exactly 100% because of rounding. MVPA=moderate to vigorous physical activity.*Study city aimed to collect accelerometer data in the total sample. †Study city aimed to collect accelerometer data in a fixed proportion of the total sample. ‡Average for valid days.

***Table 1:* Descriptive statistics of sample sociodemographic characteristics and accelerometer based moderate to vigorous physical activity**

transport density, public park density, and distance to nearest transport. Table 2 provides definitions of variables and key terms. Table 3 presents descriptive findings for environmental variables overall and by city.

Covariates included age, sex, education (<12 years or high school level, high school graduation, and university degree or higher), marital status (married or living with partner *vs* other), employment status (unemployed *vs* employed), city, accelerometer wear time, and SES of administrative unit (low *vs* high).

Statistical analysis

Associations between environmental variables and physical activity (min/day) were estimated with generalised additive mixed models (GAMMs) with gamma variance and logarithmic link functions, appropriate for the sampling strategy and distributional properties of the outcome variable.[19,20] These models also allowed for the simultaneous estimation of the amount of variability in participants' individual MVPA attributable to factors at city level, administrative unit level (within city), and individual level. Covariate-adjusted single environmental variable (SEV) and multiple environmental variable (MEV) GAMMs were estimated. The MEV GAMM included only statistically significant ($p<0·05$) buffer-specific environmental correlates for each buffer size. Environmental variables were entered simultaneously in the MEV GAMMs as collinearity was not problematic. Curvilinearity of relations was assessed with thin-plate spline smooth terms.[20] Separate GAMMs were run to estimate environmental features by study city interaction effects to assess whether the associations of environmental features with MVPA differed across cities. The significance of interactions was assessed by comparison of Akaike information criterion values of models with and without an interaction term (≥10 difference indicated significance).[21] To quantify effect sizes of significant environmental correlates of MVPA, covariate-adjusted differences in weekly minutes of MVPA were estimated between participants living in buffers with the lowest 5% and highest 5% values of environmental correlates and between participants living in areas with values of environmental correlates corresponding to the lowest and highest average city-level values. We also expressed these differences in activity in percentages of the amount needed to comply with the WHO physical activity guidelines (ie, percentages of 150 min/week of MVPA).[22]

To assess built environment contributions to differences in physical activity at the city level, administrative unit level, and person level, three-level GAMMs with random intercepts at the city and administrative unit levels adjusted and unadjusted for environmental features were estimated, and the percentage reductions in residual variances were computed. As only 220 (2·2%) of 10 008 cases had

www.thelancet.com **Published online April 1, 2016 http://dx.doi.org/10.1016/S0140-6736(15)01284-2**

	All cities	Ghent, Belgium	Curitiba, Brazil	Bogota, Colombia	Olomouc, Czech Republic	Aarhus, Denmark	Hong Kong, China	Cuernavaca, Mexico	North Shore, New Zealand	Waitakere, New Zealand	Wellington, New Zealand	Christchurch, New Zealand	Stoke-on-Trent, UK	Seattle, WA, USA	Baltimore, MD, USA
Net residential density (per km²)—1·0 km buffer															
Mean	6682 (12 522)	7853 (6795)	5993 (3950)	9273 (3248)	18 086 (9808)	7115 (5649)	57 322 (25 592)	2237 (933)	1764 (739)	2029 (738)	4203 (4973)	1658 (360)	4579 (1447)	3015 (3574)	2498 (2330)
Median	2493 (1529–2493)	5214 (1240–12 665)	4652 (3851–6832)	8995 (6677–11 726)	18 810 (9424–24 512)	4635 (2205–11 750)	65 456 (35 629–78 709)	2202 (1597–2730)	1735 (1619–1921)	2126 (1519–2484)	1909 (1506–5643)	1544 (1438–1925)	4161 (3766–4916)	2183 (1292–3180)	1585 (791–3934)
Net residential density (per km²)—0·5 km buffer															
Mean	7025 (13 355)	7246 (6894)	6338 (5262)	12 997 (5147)	19 219 (15 579)	8398 (7633)	57 276 (30 728)	2619 (1964)	1748 (382)	2665 (1476)	3559 (3014)	1669 (447)	4471 (1674)	3328 (4471)	3424 (4505)
Median	2729 (1530–6214)	5190 (1561–9894)	4776 (3542–6936)	12 475 (9120–15 154)	14 880 (8070–25 457)	4661 (1916–16 792)	60 912 (29 896–86 372)	2309 (1467–3267)	1790 (1570–2015)	2462 (1891–2959)	1767 (1471–4930)	1552 (1339–1982)	3979 (3501–4923)	2244 (1214–3215)	1774 (786–4294)
Intersection density (per km²)—1·0 km buffer															
Mean	76 (57)	84 (62)	76 (16)	227 (91)	67 (20)	83 (22)	128 (58)	146 (47)	27 (7)	28 (10)	42 (15)	35 (6)	93 (29)	71 (22)	55 (28)
Median	65 (38–94)	73 (35–92)	72 (64–83)	234 (153–301)	67 (54–80)	86 (72–98)	129 (85–172)	135 (111–168)	27 (23–32)	28 (24–31)	43 (34–52)	36 (32–40)	87 (75–114)	71 (56–85)	53 (38–67)
Intersection density (per km²)—0·5 km buffer															
Mean	87 (69)	86 (61)	84 (23)	249 (111)	75 (25)	105 (31)	174 (79)	174 (72)	31 (12)	35 (18)	42 (21)	37 (9)	113 (37)	76 (28)	64 (40)
Median	71 (40–109)	74 (36–109)	80 (68–94)	222 (163–342)	75 (60–88)	105 (85–125)	162 (122–216)	166 (119–234)	31 (21–40)	33 (24–40)	40 (26–54)	36 (30–43)	116 (81–133)	77 (57–95)	59 (40–78)
Proportion of retail and civic land area to total buffer area—1·0 km buffer*															
Mean	0·17 (0·24)	0·14 (0·13)	0·16 (0·10)	0·12 (0·09)	0·06 (0·06)	0·52 (0·42)	0·54 (0·24)	0·17 (0·12)	0·12 (0·27)	0·10 (0·13)	0·31 (0·52)	0·18 (0·31)	0·04 (0·04)	0·08 (0·06)	0·12 (0·13)
Median	0·09 (0·04–0·20)	0·09 (0·03–0·25)	0·13 (0·10–0·20)	0·08 (0·04–0·18)	0·04 (0·02–0·07)	0·44 (0·16–0·80)	0·58 (0·47–0·68)	0·15 (0·07–0·27)	0·08 (0·04–0·14)	0·07 (0·03–0·11)	0·11 (0·05–0·30)	0·06 (0·03–0·13)	0·02 (0·01–0·05)	0·06 (0·04–0·10)	0·08 (0·04–0·17)
Ratio retail and civic land area to total buffer area—0·5 km buffer*															
Mean	0·17 (0·33)	0·16 (0·21)	0·14 (0·11)	0·10 (0·08)	0·07 (0·09)	0·74 (0·76)	0·73 (0·44)	0·17 (0·16)	0·14 (0·31)	0·08 (0·15)	0·28 (0·60)	0·08 (0·30)	0·05 (0·07)	0·07 (0·09)	0·11 (0·21)
Median	0·07 (0·01–0·18)	0·09 (0·01–0·24)	0·13 (0·06–0·19)	0·07 (0·04–0·14)	0·04 (0·01–0·06)	0·49 (0·15–1·07)	0·65 (0·51–0·96)	0·14 (0·01–0·27)	0·06 (0·01–0·17)	0·01 (0·00–0·09)	0·07 (0·00–0·21)	0·02 (0·00–0·08)	0·01 (0·00–0·06)	0·04 (0·00–0·10)	0·05 (0·00–0·13)
Public transport density (per km²)—1·0 km buffer†															
Mean	15·8 (12·9)	9·4 (6·3)	25·8 (7·3)	2·2 (2·6)	13·6 (5·4)	9·4 (4·6)	12·0 (8·2)	29·1 (24·4)	19·0 (7·3)	9·0 (7·1)	16·6 (8·6)	16·0 (9·0)	25·3 (7·9)	15·9 (9·7)	16·9 (13·6)
Median	14·3 (6·6–21·9)	7·7 (1·5–15·4)	25·0 (20·4–29·8)	1·2 (0·0–3·3)	14·5 (9·1–17·8)	9·1 (5·9–12·7)	13·0 (4·0–16·9)	26·0 (11·4–39·4)	20·1 (14·4–24·8)	6·9 (4·5–12·7)	14·9 (11·8–22·0)	16·2 (9·4–20·0)	24·0 (19·1–31·5)	15·7 (9·0–22·8)	15·7 (7·4–24·5)

(Table 2 continues on next page)

	All cities	Ghent, Belgium	Curitiba, Brazil	Bogota, Colombia	Olomouc, Czech Republic	Aarhus, Denmark	Hong Kong, China	Cuernavaca, Mexico	North Shore, New Zealand	Waitakere, New Zealand	Wellington, New Zealand	Christchurch, New Zealand	Stoke-on-Trent, UK	Seattle, WA, USA	Baltimore, MD, USA
(Continued from previous page)															
Public transport density (per km²)—0·5 km buffer†															
Mean	17·0 (17·0)	10·4 (9·8)	24·0 (11·5)	2·4 (4·5)	15·0 (9·1)	10·9 (7·1)	13·0 (13·2)	33·3 (35·6)	20·1 (12·2)	8·4 (7·5)	19·4 (12·2)	16·8 (14·7)	28·2 (13·7)	16·8 (13·1)	18·0 (17·7)
Median	14·1 (4·2–24·2)	8·6 (3·3–14·3)	23·5 (16·2–31·2)	0·0 (0·0–2·7)	14·4 (9·0–21·0)	10·8 (5·9–16·4)	11·2 (0·0–20·0)	25·2 (0·0–49·0)	20·0 (12·8–27·7)	7·6 (2·5–12·5)	20·7 (12·8–26·1)	15·8 (5·1–22·5)	26·4 (19·1–36·0)	16·8 (5·0–26·9)	15·5 (0·0–26·7)
Street network distance to nearest transport stop or station (m)															
Mean	421 (638)	317 (284)	178 (111)	1863 (1525)	265 (173)	303 (230)	426 (350)	501 (659)	245 (216)	343 (266)	222 (284)	300 (240)	212 (136)	382 (439)	639 (1017)
Median	242 (124–429)	258 (150–360)	161 (83–249)	1193 (557–3385)	232 (159–350)	235 (151–384)	353 (205–506)	239 (102–591)	186 (93–338)	297 (153–468)	147 (60–301)	242 (118–415)	189 (100–299)	227 (128–449)	238 (117–550)
Number of parks contained or intersected by buffer of 1·0 km															
Mean	5·5 (6·5)	3·8 (3·6)	6·0 (4·6)	25·4 (13·3)	3·7 (4·4)	4·4 (3·4)	13·5 (10·0)	1·5 (2·1)	12·3 (6·5)	8·7 (3·9)	4·6 (2·5)	5·6 (2·5)	2·8 (1·5)	3·8 (2·9)	2·4 (2·1)
Median	4·0 (1·0–7·0)	3·0 (1·0–6·0)	5·0 (2·0–8·0)	24·0 (14·0–34·0)	2·0 (1·0–5·0)	4·0 (2·0–6·0)	11·0 (5·0–19·0)	1·0 (0·0–2·0)	11·0 (8·0–16·0)	8·0 (6·0–11·0)	4·0 (3·0–7·0)	6·0 (3·0–7·0)	2·0 (2·0–4·0)	3·0 (1·0–6·0)	2·0 (1·0–3·0)
Number of parks contained or intersected by buffer of 0·5 km															
Mean	1·8 (2·3)	1·2 (1·3)	2·0 (2·3)	7·4 (4·6)	1·1 (1·6)	1·3 (1·4)	4·0 (3·5)	0·6 (0·9)	4·1 (2·7)	3·5 (2·6)	1·4 (1·0)	1·6 (1·2)	1·3 (0·9)	1·2 (1·2)	0·9 (1·0)
Median	1·0 (0·0–2·0)	1·0 (0·0–2·0)	1·0 (0·0–3·0)	7·0 (4·0–10·0)	1·0 (0·0–2·0)	1·0 (0·0–2·0)	3·0 (1·0–5·0)	0·0 (0·0–1·0)	4·0 (2·0–6·0)	3·0 (2·0–5·0)	1·0 (1·0–2·0)	1·0 (1·0–2·0)	1·0 (1·0–2·0)	1·0 (0·0–2·0)	1·0 (0·0–1·0)

Data are mean (SD) and median (first quartile to third quartile). *Descriptive statistics were computed after assigning a value of 3·1 to all participants with values greater than 3·1 (one value truncated for 1·0 km buffer measure and 22 for 0·5 km buffer measure).†Measured by number of transport options.

Table 2: **Descriptive statistics of objectively-assessed environmental attributes**

	Buffer size (km)	exp(b)	exp (95% CI)	p value
Net residential density (1000 dwellings/km²)				
SEV	1·0	1·006	1·003–1·009	0·001
MEV	1·0	1·004	1·001–1·007	0·006
Intersection density (100 intersections/km²)				
SEV	1·0	1·069	1·011–1·130	0·019
MEV	1·0	..	..	..
Proportion of retail combined and civic land area to total buffer area				
SEV	1·0	1·056	0·964–1·157	0·238
MEV	1·0	..	..	..
Public transport density (10 transport points/km²)				
SEV	1·0	1·037	1·018–1·056	0·0007
MEV	1·0	1·030	1·011–1·049	0·006
Number of parks contained or intersected by buffer (10 parks/km²)*				
SEV	0·5	1·146	1·033–1·272	0·010
MEV	0·5	1·111	1·000–1·233	0·046
Street network distance to nearest transport stop (1000 m)				
SEV	1·0	1·033	0·996–1·071	0·078
MEV	1·0	..	..	..

All regression coefficients adjusted for respondents' age, sex, marital status, educational attainment, employment status, administrative-unit socioeconomic status, accelerometer wear time, and study city. Units of measurement shown after variable name in parentheses. exp(b) is the proportional increase in physical activity associated with a 1 unit of measurement increase in the predictor (eg, 1000 dwellings/km² is 1 unit of measurement for net residential density). Only results for the buffer size (1·0 km or 0·5 km) showing the strongest relationships with physical activity are reported. SEV=single environmental variable; MEV=multiple environmental variable (only significant environmental correlates included); exp(b)=antilogarithm of regression coefficient; exp (95% CI)=antilogarithm of confidence intervals. *Adjusted for net residential density, intersection density, and transport density.

Table 3: **Pooled associations of environmental attributes with daily minutes of moderate to vigorous physical activity by model (n=6679)**

missing data, analyses were only done for complete cases. All analyses used R.

Role of the funding source

Funding for coordination of the IPEN adult study was provided by the National Cancer Institute of National Institutes of Health (CA127296), with studies in each country funded by different sources. Funders were not involved in planning or executing the study and they were not involved in preparing the manuscript. JFS had full access to all of the data in the study and had the final responsibility for the decision to submit for publication.

Results

On average, participants accumulated about 37 min/day of MVPA. Baltimore (USA) had the lowest average value (29·2 min) and Wellington (New Zealand) had the highest average value of MVPA (50·1 min; table 1).The standard deviation of MVPA at the city level was 6·3 min/day, at the administrative unit level was 4·6 min/day, and at the person level was 24·4 min/day. Higher variability at the person level was expected. Four of six environmental variables were

	5% lowest values of environmental features	5% highest values of environmental features	Differences in weekly minutes of MVPA between lowest 5% and highest 5% values of environmental correlate (95% CI)	Lowest average study-city value for environmental features	Highest average study-city value for environmental features	Differences in weekly minutes of MVPA between lowest and highest average study-city values of environmental features (95% CI)
SEV						
Net residential density—1·0 km buffer	710	21 078	29 (12–46) 19% of PAG	1658·0	57 322·0	89 (38–147) 59% of PAG
Intersection density—1·0 km buffer	16	198	31 (5–60) 21% of PAG	27·0	227·0	34 (5–68) 23% of PAG
Public transport density—1·0 km buffer	0	35	32 (17–52) 21% of PAG	2·2	29·1	24 (12–36) 16% of PAG
Number of parks contained or intersected by 0·5 km buffer	0	6	21 (5–37) 14% of PAG	0·6	7·4	24 (5–43) 16% of PAG
MEV						
Net residential density—1·0 km buffer	710	21 078	49 (15–86)*	1658·0	57 322·0	89 (29–161)*
Public transport density—1·0 km buffer	0	35	33% of PAG	2·2	29·1	59% of PAG
Net residential density—0·5 km buffer	652	28 917	48 (6–78)†	1669·0	57 276·0	68 (11–144)†
Public transport density—0·5 km buffer	0	46	32% of PAG	2·4	33·3	45% of PAG
Number of parks contained or intersected by 0·5 km buffer	0	6	..	0·6	7·4	..

The residual variability in MVPA at a specific level is expressed in standard deviations (after adjusting for sociodemographics and accelerometer-wear time). Only results for the buffer size (1·0 km or 0·5 km) showing the strongest relationships with physical activity are reported. MVPA=moderate to vigorous physical activity. SEV=single environmental variable. MEV=multiple environmental variable (only significant environmental correlates included). PAG=physical activity guidelines (total recommended amount of 150 min/week of MVPA).[22] *Combined effect of net residential density and public transport density. †Combined effect of net residential density, public transport density, and number of parks contained or intersected by 0·5 km buffer.

Table 4: **Differences in estimated MVPA between participants with low and high values for significant environmental correlates**

significantly associated ($p<0·05$) with MVPA in the SEV models (table 3). These four variables explained 0–11% of MVPA variability at the city level and explained 7–11% at the administrative unit levels, but virtually no variance at the person (within administrative unit) level. Net residential density, intersection density, public transport density, and number of parks within participants' buffers were linearly and positively related with MVPA. Both buffer sizes were tested and with the exception of number of parks, stronger relations were noted for variables calculated for 1·0 km than for 0·5 km buffers. Relations for variables calculated for the most significant buffers (1·0 km or 0·5 km) are reported (table 3).

After we adjusted for other environmental variables in the multiple environmental variable (MEV) models, net residential density and public transport density remained significant, positive, and linear correlates of MVPA for both buffer sizes. Additionally, number of parks significantly contributed to explaining MVPA in the model based on 0·5 km buffers (table 3). The MEV models explained 11–12% of the total MVPA variance.

Based on the absence of significant interactions between environmental and city features, we can conclude that associations were generalisable across study cities, with the exception of number of parks in 0·5 km buffers. Specifically, positive associations between parks within 0·5 km buffers and physical activity in the SEV model were reported only in Ghent, Belgium (exp[b]=1·772; 95% CI 1·177–2·669; p=0·006) and Seattle, USA (exp[b]=2·064; 95% CI 1·399–3·045; $p<0·001$). After we adjusted for other environmental variables, the park counts by city interaction was no longer significant and a significant positive association of park counts with MVPA was reported across all cities (table 3). Thus, we noted evidence of similar relations of urban environment variables and physical activity across diverse cities. Analyses examining the shape of associations reported no sufficient evidence for curvilinearity of effects. Therefore, we concluded that environment associations with physical activity were linear.

Table 4 reports the estimated differences in minutes per week of MVPA between participants living in areas at the lowest and highest 5% of the sample values for specific significant environmental correlates, including areas with values of environmental correlates equal to those of the cities with the lowest and highest average values. The differences in MVPA between residents living in areas at the lowest and highest 5% for specific single environmental features ranged from 21 to 32 min/week. The differences in MVPA between participants living in areas with values of single environmental correlates equal to those of study cities with the lowest and highest average values ranged from

24 min/week to 89 min/week. This finding corresponded to meeting between 16% and 59% of the recommended 150 min/week of physical activity. The estimated differences in minutes per week of MVPA between participants living in areas with all significant environmental correlates at the lowest and highest average city values was 68 min/week when comparing the lowest 5% versus highest 5% neighbourhood buffer values. A difference of 89 min/week was found when comparing the lowest versus highest average city values. These differences are equivalent to meeting 45–59% of the 150 min/week physical activity guidelines.

Discussion

This multicountry study identified urban environmental attributes that accounted for large differences in adults' physical activity. Combinations of environmental features generally explained more variation in physical activity than single variables, suggesting that a comprehensive approach is needed to design activity supportive neighbourhoods. When we compared participants living in the 5% most with the 5% least activity supportive neighbourhoods, SEV models accounted for a smaller number of minutes of MVPA compared with models including all significant environmental variables. When we compared participants living in areas similar to the cities with the most versus the least activity supportive environments, single variables accounted for a difference of 24–89 weekly minutes of physical activity, compared with 68–89 min for combined variable models. Living in the most activity-friendly environments could help the average resident to achieve 45–59% of the 150 min/week of physical activity recommended guidelines.[22] These observed effect sizes suggest that designing urban environments to be activity-supportive could have large effects on physical activity and those effects can be expected to generally apply to adults living in the neighbourhoods. Such widespread and long-term effects are in contrast to programmes that target individuals and tend to reach small numbers of people and produce short-term effects.[23]

Three environmental attributes had significant independent associations with total MVPA in the MEV and SEV models: net residential density, public transport density, and park density. Net residential density's strong associations were consistent with those shown in many other studies.[24] High residential density is generally deemed to be necessary for other components of walkability because local patronage is needed to support nearby shops and services and enough riders to support frequent transport service.[25] Density of public transport stops was independently related to total activity. Public transport density was notably a significant correlate of MVPA but distance to nearest transport stop was not significant. One interpretation is that having various options for transport lines makes residents more likely to walk to a transport facility that meets their needs. Public transport access has been studied less often in relation to physical activity.[6,24] Good transport access is a requirement for living a less car-dependent lifestyle.[26] Particularly in the middle-income cities in the sample, car ownership was low and in these settings, active transport, such as walking and cycling could represent necessity and not choice. Thus, research into the role of public transport access in car owners and non-owners would be useful. The third significant variable in the final model was number of parks in the 0·5 km buffer. Park density is a relatively consistent correlate of adult physical activity.[6,24] Although parks are usually thought of as supporting recreational activities through facilities and aesthetics, nearby parks can also be a destination for active transportation. Thus, the most well supported environmental variables were probably related to total physical activity through their effects on both recreational and transportation activities.

All reported associations were linear so we did not note a threshold or a point of diminishing returns for environmental attributes. Present findings, with probably the widest range of environmental variables yet reported, support a recommendation that higher levels of residential density, public transport access, and local parks should be recommended when designing physical activity supportive environments.

The measure of mixed land use was not related to physical activity in our study, although this factor is one of the more consistent correlates of physical activity.[6,24] Proximal (eg, within 1 km buffers) retail shops and services provide frequently used destinations that stimulate regular walking. Because of the large variation in the proportion of retail and civic land use to buffer area within and between countries, the non-significant results were surprising. One possible explanation is the limitations of the GIS-based measure. Because most countries only had data for the land area devoted to each use, as opposed to building floor area, we were unable to tell whether each use was operating on part of the parcel or on several floors of a building covering the entire parcel. A related limitation was that the data were based on number of parcels, not on number of shops or offices, which might be more strongly related to frequency of use and thus to physical activity. In middle-income cities with a high prevalence of walking for transport, many shops were not registered, including those in permanent buildings as well as informal markets and street vendors. These data limitations could have reduced the power to detect an association.

Intersection density is an indicator of street connectivity that provides direct pathways for pedestrians and vehicles. This variable was significant in SEV models, but not in the full models, suggesting a confounding effect with other variables, such as residential density or public transport density.[25]

An important finding was the strong support for the similarity or generalisability of associations between built environment and physical activity across countries diverse in income, culture, and activity supportiveness. The diversity of the study cities in climate, demographics,[10] and built environments has been documented in previous publications.[18] Present results suggest systematic principles of environments that support physical activity apply on a global scale.[19] Generalisable associations with physical activity were also reported in analyses of self-reported environment measures in the same study.[19]

Study strengths included the use of objective measures of both urban environments and physical activity, comparable variables across diverse countries, assessment of two buffer sizes, and analyses that tested for curvilinear effects and generalisability of associations across cities. Limitations included a small number of environmental variables that could be assessed through common environmental measures, likely variations in the quality of those measures across countries, scarce representation of low-income countries, a modest sample size in some cities that reduced power to detect differences in associations across cities, and cross-sectional design. Another limitation is that covariates, such as sex and education, might have different meanings and functions across countries. Other patterns of association might be noted with other age groups and built environment correlates are expected to differ by physical activity outcome. Absence of adjustment for self-selection into neighbourhoods is a frequent criticism of built environment studies but not all countries in the present study included measures that assessed reasons for neighbourhood selection.[27]

Our recommendations for future research are to expand the number of countries, especially low-income countries, in which associations between urban environment and physical activity are assessed; to develop objective measures for other environmental attributes relevant to physical activity, such as sidewalks, pedestrian zones, bicycle facilities, and factors affecting intersection quality (eg, crosswalks, pedestrian signals, and traffic calming); and to implement prospective studies and quasi-experimental evaluations of improvements in urban environments.

A recommendation for practice is to make the creation of activity supportive environments a regular function of public health agencies globally through work with sectors outside of public health. Regular assessment and reporting (ie, surveillance) of the quality of activity supportive environments is a vital component of efforts to foster creation of these environments. Health department staff should seek training, develop collaborations, and become advocates for improved policies in city planning, transportation, and parks agencies.

Design of urban environments has the potential to contribute nearly 90 min/week of physical activity, which is 60% of the 150 min/week recommended in physical activity guidelines. These potentially large effects of built environments were reported to apply similarly across ten diverse countries, indicating that urban design should be a globally relevant public health priority. Building, retrofitting, and maintenance of physical activity supportive features in cities worldwide to increase residential density, provide good transport service, and ensure access to parks would be expected to substantially increase physical activity in the population on a permanent basis and contribute to meeting the UN's goals to reduce non-communicable diseases.[2,3] Our study findings provide an impetus for public health proponents to collaborate with other sectors, including environmental sustainability groups, to promote physical activity supportive development as a means to reduce energy consumption, greenhouse gas emissions, and air pollution,[11,28] while achieving health and economic benefits.[29]

Contributors

JFS was the lead author and led study design, international data coordination, securing funding for international coordination, literature search, and data interpretation. EC contributed to study design, securing funding, literature search, data collection, data analysis, data interpretation, drafted sections, and edited the manuscript. TLC contributed to study design, international data coordination, data collection, data interpretation, drafted sections, and edited the manuscript. MAA contributed to international data coordination, creation of GIS variables, drafted sections, and edited the manuscript. LDF contributed to study design, international data coordination, creation of GIS variables, data interpretation, drafted sections, and edited the manuscript. DS contributed to literature search, site selection, data collection, drafted sections, and edited the manuscript. GS contributed data collection, drafted sections, and edited the manuscript. JS contributed to data collection, drafted sections, and edited the manuscript. MP contributed to securing funding, site selection, study design, data collection, and edited the manuscript. KLC contributed to study design, international data coordination, secured funding, data collection, led creation of accelerometer variables, drafted sections, and edited the manuscript. RD contributed to securing funding, data collection, and edited the manuscript. JK contributed to study design, international data coordination, secured funding, and edited the manuscript. P-CL contributed to data collection and edited the manuscript. JM contributed to securing funding, data collection, and edited the manuscript. RR contributed to securing funding, data collection, and edited the manuscript. OLS contributed to securing funding, data collection and edited the manuscript. GS contributed to securing funding, data collection, and edited the manuscript. JT contributed to securing funding, data collection, and edited the manuscript. DVD contributed to data collection and edited the manuscript. IDB contributed to study design, international data coordination, securing funding, data collection, and edited the manuscript. NO contributed to study design, international data coordination, securing funding, data interpretation, and edited the manuscript.

Declaration of interests

JFS has received grants and personal fees from the Robert Wood Johnson Foundation outside of the present study, grants and non-financial support from Nike outside of this Article, and is a consultant and receiver of royalties from SPARK Programs of School Specialty. LDF is principal owner of Urban Design 4 Health. All other authors declare no competing interests.

Acknowledgments

All authors declare financial support for this study from the National Cancer Institute (NCI) of the National Institutes of Health (NIH). Data collection in Hong Kong was supported by the HK Research Grants Council GRF grants (HKU740907H and 747807H) and the University of Hong Kong University Research Council Strategic Research Theme (Public Health). US data collection and coordinating centre processing was supported by the NIH grants R01 HL67350 (National Heart, Lung, and Blood Institute) and R01 CA127296 (NCI). The study in Bogota was funded by Colciencias grant 519_2010, Fogarty, and CeiBA. EC was supported by an Australian Research Council Future Fellowship (FT3 140100085). NO was supported by National Health and Medical Research Council Program Grant 569940, 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 Ministry of Education, Youth and Sports (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 Centers for Disease Control and Prevention (CDC) Foundation, which received an unrestricted grant from The Coca-Cola Company. The UK study was funded by the Medical Research Council under the National Preventive Research Initiative. DS was supported by a training grant from the CDC Foundation. Kavita A Gavand at University of California, San Diego, CA, USA, supported the preparation and submission of this manuscript.

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Our health is a function of where we live

Published Online
April 1, 2016
http://dx.doi.org/10.1016/S0140-6736(16)00348-2

See Online/Articles
http://dx.doi.org/10.1016/S0140-6736(15)01284-2

In *The Lancet,* James Sallis and colleagues[1] report significantly higher physical activity levels among residents where the built environment is supportive of physical activity. This study is the largest to date and includes data from five continents (6822 adults) and makes a completely objective assessment of both the attributes of the built environment and the physical activity outcomes. The following four built environments were positively and linearly associated with higher physical activity levels in the single environment model: more public parks within walking distance (0·5 km) from residence, which were free and open to all; higher density of public transport such as number of bus, rail, or ferry stops and stations divided by the land area; higher net residential density; and higher number of street intersections that are pedestrian accessible.

Sallis and colleagues' Article is uniquely different, rigorous, and robust, when compared with previous published studies. Earlier studies of built environment and physical activity[2] have struggled with methodological shortcomings: single country or continent, small sample sizes, and use of self-reported physical activity and perception of environment, which do not allow for an accurate quantification of either physical activity or structural environmental attributes, which increase or hinder physical activity.[2] Self-reported physical activity levels are influenced by age, sex, culture, and recall bias. Sallis and colleagues used measurements from geographic information systems and accelerometers to assess environment and physical activity objectively. They noted a difference of 68–89 min of moderate and vigorous physical activity (MVPA) per week between the least and most supportive built environment areas, a substantial difference that translates into 45–59% of MVPA recommended per week by WHO.[3]

Lee and colleagues[4] estimated in a conservative calculation that physical inactivity caused 9% of premature mortality, that is, more than 5·3 million deaths in 2008. A similar percentage of non-communicable diseases can be attributed to physical inactivity, such as coronary artery disease (6%, 95% CI 3·2–7·8), strokes and diabetes (7%, 3·9–9·6), breast cancer (10%, 5·6–14·1), and colon cancer (10%, 5·7–13·8).[4] On the basis of the physical activity distribution in Sallis and colleagues' Article, almost two-thirds of physically inactive people would fulfil international guidelines if they added 10 min of MVPA every day (Cerin E, University of Hong Kong, personal communication). According to Lee and colleagues,[4] 3·6 million deaths would be prevented each year worldwide if two-thirds of inactive people increased their activity to the level recommended in the guidelines. Given that Sallis and colleagues noted a difference of 68–89 min of MVPA per week between the least and most supportive built environments and given that the current environment of all participants might vary across a spectrum of supportive and unsupportive of physical activity, we estimate that total health gained by changing to optimal activity-friendly environments will be close to 2 million fewer deaths and around 3% fewer non-communicable diseases (in other words, about 50% lower physical activity associated non-communicable diseases).

Traditionally, some of the most pedestrian-friendly, physical activity-friendly, and cycle-friendly cities in the world were built or developed not for specific physical activity or health considerations, but for larger public good, and common civic sense. Wide pedestrian pathways (shaded with trees to counter the hot weather in tropical countries), cycling or bike lanes, green spaces for walking, and parks and community or sports centres were constructed many decades ago for public good. Delhi and Mumbai in India were such cities: they were beautiful pedestrian-friendly cities, but rampant

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new construction has undermined their pedestrian friendliness and cycling friendliness.[5,6] Similarly, the well known Danish bike lane system—which enables 25% of the population to cycle to work[7]—provides substantial health benefits. Mortality is 30% lower in cycle commuters compared with those who use passive transport.[8] Most bike lanes were constructed 50 years ago because visionary politicians realised that cyclists caused less pollution and less traffic congestion than cars, and new cars were taxed 180%.

Large sums of public money are spent on building or remodelling roads, cycling, and walking paths for good or ill. For example, the contentious so-called bus rapid transport in Delhi cost US$22·5 million.[9,10] Similarly, the small city Førde, in Norway, has assigned $150 million to build bike infrastructure with no money for evaluation. Well planned multiperspective assessments (or evaluations) should be done for all new, existing, and old urban environment projects.

Historically, town planning and built environments have had major impacts on infectious diseases such as cholera, rheumatic fever, and tuberculosis.[11] Today's reality is that large-scale and rural–urban migration, often of people in distress, is leading to unplanned overcrowded habitation and poor sanitation in many developing countries, contributing to outbreaks of infectious diseases and also increasing rates of non-communicable diseases.[6,12,13] Sallis and colleagues present clear evidence for the role of the urban built environment in enhancing physical activity levels of entire populations, across socioeconomic classes and cultures, and thereby preventing non-communicable disease. This evidence puts greater responsibility on town planners. Other vital attributes of the built environment that support physical activity and are taken for granted in all the countries of Sallis and colleagues' study, might not be noted in many other developing countries and need urgent attention—safety, pedestrian priority, availability of adequately wide, usable, unencroached pedestrian pathways, convenience and safety in cycling, and adequate capacity in public transport.

Ongoing and long-term multiperspective evaluations of existing urban built environments should be an integral part of urban planning and governance. We need interventions to counter the rapidly growly inactivity that urbanisation leads to, by providing environments that change the way we live our daily lives. It is high time that built environments provide the quadruple boost towards health, environment, equity (or public good), and habitat.

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We declare no competing interests.

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