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Determining thresholds for spatial urban design and transport features that support walking to create healthy and sustainable cities: findings from the IPEN Adult study

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An essential characteristic of a healthy and sustainable city is a physically active population. Effective policies for healthy and sustainable cities require evidence-informed quantitative targets. We aimed to identify the minimum thresholds for urban design and transport features associated with two physical activity criteria: at least 80% probability of engaging in any walking for transport and WHO's target of at least 15% relative reduction in insufficient physical activity through walking. The International Physical Activity and the Environment Network Adult (known as IPEN) study (N=11615; 14 cities across ten countries) provided data on local urban design and transport features linked to walking. Associations of these features with the probability of engaging in any walking for transport and sufficient physical activity (≥ 150 min/week) by walking were estimated, and thresholds associated with the physical activity criteria were determined. Curvilinear associations of population, street intersection, and public transport densities with walking were found. Neighbourhoods exceeding around 5700 people per km², 100 intersections per km², and 25 public transport stops per km² were associated with meeting one or both physical activity criteria. Shorter distances to the nearest park were associated with more physical activity. We use the results to suggest specific target values for each feature as benchmarks for progression towards creating healthy and sustainable cities.

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This is the second in a [Series](#) of four papers about urban design, transport, and health

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Introduction

UN Sustainable Development Goal (SDG) 3 explains the importance of healthy living and wellbeing at all ages,¹ which in turn require healthy and sustainable cities consistent with SDG 11. There is strong evidence for many health benefits from regular physical activity.² Therefore, an essential characteristic of a healthy and sustainable city is a physically active population.³

According to WHO physical activity guidelines, adults can achieve substantial health benefits by regularly doing as little as 150 min per week of moderate-intensity physical activity,⁴ including walking.⁵ However, more than a quarter of adults worldwide do not meet these physical activity recommendations.⁶ The importance of walking as a means to accumulate health-enhancing physical activity stems from its popularity, universality, equitability, and accessibility.⁵ Walking is the most reported type of physical activity in adults who meet WHO physical activity guidelines.^{5,7–9} People walk for various purposes (eg, work, recreation, and transport) and in various settings. Provided that environments are sufficiently safe,¹⁰ walking is generally appropriate for all sexes, ages, ethnicities, socioeconomic groups, and those with common age-related chronic conditions.^{11–13} Consequently, promoting walking could reduce the health disparities in a population due to physical inactivity, and achieve several related UN Sustainable Development Goals, including SDGs 3, 5 (achieving gender equality and empowering all women and girls), and 10 (reducing within-country and between-country inequalities).¹⁴

Apart from contributing to healthier and more equitable societies, a specific type of walking—walking for transport—is important for achieving additional UN SDGs, including making cities inclusive, safe, resilient, and sustainable (SDG 11), and mitigating climate change (SDG 13).¹⁵ Since the 1970s, many countries, especially middle-income to high-income countries, have had sharp increases in fossil-fuel-dependent industrialisation, technological innovation, and urban sprawl, leading to substantial population shifts towards sedentary occupations, individualised motorised transport, and motor vehicle dependency.^{6,16} Unsurprisingly, these trends have led to declines in physical activity and increases in air pollution and greenhouse gas emissions, with emissions being the primary cause of climate change.¹⁶ Because of widespread car ownership and car-centric urban design, people now frequently drive for short trips that could be walked or cycled.^{17,18} The recent increase in shared mobility services globally (eg, Uber or Lyft) has also decreased the short trips usually done by walking and cycling, and increased traffic congestion.¹⁹

If people are to walk more, they need urban environments that encourage and support walking.^{10,20,21} Urban design and transport features—including higher residential density, mixed land use, street connectivity, and better access to public transport, amenities, and parks—have been associated with more walking,^{22–27} especially walking for transport.^{22–24,28} However, most of the relevant evidence is from high-income countries. A review of the few cross-sectional studies from

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low-income and middle-income countries concluded that population density and access to services were inconsistently associated with physical activity and that mixed land-use was positively associated with active transport.^{29,30}

The evidence that compact neighbourhoods with easy access to amenities, parks, and public transport underpin a healthy and sustainable city is rarely effectively incorporated into city planning policy, which perpetuates urban sprawl and automobile dependency, along with all their deleterious effects on human and planetary health.³¹ In the first paper in this Series, Lowe and colleagues³² find that many cities worldwide do not have measurable policy targets that would facilitate the monitoring of progress on city planning interventions that influence health and health-related behaviours such as walking. Such targets would inform practice and aid accountability. This absence of city planning policy could partly be due to many countries not having measurable targets for reducing health risk factors and defined multisectoral strategies to achieve them, as evidenced in a 2020 study of national physical activity policies across 76 countries.³³ The absence of measurable city planning policy targets also stems from the dearth of clear guidance on thresholds of urban design and transport features needed to achieve the desired outcomes.^{34,35} For example, although more dense environments (dense in both infrastructure and population) are typically associated with more walking,^{23,24,28} increases in density beyond some threshold values might not yield additional benefits and can even deter walking.^{36,37} To create healthy and sustainable cities, wherever possible, thresholds should be based on the empirical evidence of relationships of urban design and transport features with health-related behaviours and outcomes. This topic has been identified as an important area of research by some authors.³⁸

Transport planners have been looking for reliable density thresholds to inform investment decisions for a long time. For example, studies conducted in the USA found that minimum net residential densities of around 2000 dwellings per km² support rail use³⁵ and 3500–4500³⁴ dwellings per km² support use of all public transport, both of which support walking. Another nationwide US study reported that a dwelling density of around 7500 per km² was associated with at least a 70% chance of walking for transport.³⁹ The study also found that walking was higher in areas with up to 100–200 intersections per km² and declined above this threshold. In an Asian ultra-dense metropolitan context, such as Seoul, the positive association between population density and walking for transport was substantially reduced at a density that exceeded 9000 to 16000 people per km².³⁷

However, most studies that examined thresholds were city-specific or country-specific. A unique dataset from which international thresholds for urban design and transport features supportive of walking can be estimated is the International Physical Activity and the Environment

Network (IPEN) Adult study. This study collected similar data on built environments and physical activity among adults from 12 countries on five continents.⁴⁰ The main motivation for establishing IPEN Adult was to enable an improved estimation of the strength and shape (forms of curvilinear relationship) of environment–physical activity relationships by capturing a range of global variation in urban environments; and by recruiting a balanced number of residents from communities that vary in key urban design features from each participating city. This sampling strategy makes the IPEN Adult study ideal for the purpose of investigating the thresholds associated with walking outcomes (eg, a certain probability of engaging in walking for transport) and their generalisability across countries.

Although studies using IPEN Adult data have reported on the strength and shape of the relationships between the built environment and various walking outcomes,^{24,41} they did not aim to quantify thresholds and their uncertainties, which is a limitation that is shared by all single-country studies (except one) on thresholds associated with walking.³⁹ Total walking—ie, the combination of walking for transport and recreation—is the most commonly reported physical activity in adults who meet WHO physical activity guidelines⁷ and, therefore, is the most policy-relevant physical activity outcome for the creation of both healthy and sustainable cities. No IPEN Adult studies investigated the relationship of built environment with total walking. The key scientific rationale for this study was to address these important knowledge gaps and subsequently inform international thresholds for the subset of spatial indicators of urban design and transport features described in this Series.³¹ We hope that these thresholds can be used to inform policies and practices to achieve healthy and sustainable cities.

The specific aims of this study were to estimate international thresholds and their uncertainties for urban design and transport features associated with two policy-relevant physical activity criteria: at least 80% probability of engaging in any walking for transport; and reaching WHO's target of at least a 15% reduction in insufficient physical activity by walking for transport or recreation for 150 min each week.⁴ Walking for transport was selected as an additional physical activity criterion to total walking (ie, total walking for transport or recreation) because it also helps to reduce air pollution and carbon emissions,⁴² and responds to changes in urban design.⁴³ A criterion of 80% probability of engaging in walking for transport was chosen because sustainable cities are typified by a high prevalence of active transport, which is relevant to achieving multiple UN Sustainable Development Goals¹⁵ and WHO physical activity goals.⁴⁵

Study design

We used data from IPEN Adult countries with harmonised spatial measures of urban design and

transport features and self-reported measures of walking for both transport and recreation.⁴⁰ The sample included 11 615 participants aged 18–66 years and recruited from 14 cities in ten countries. The two IPEN studied cities of Pamplona (Spain) and Hong Kong were excluded as they did not have objective data on the built environment or relevant data on walking. With a two-tailed probability level of 5%, the study had 80% power to detect effect sizes as small as 0·09% of explained outcome variance in pooled analyses and 4% of explained outcome variance in the smallest city-specific subsample. 11 cities were in high-income countries: Adelaide (SA, Australia); Ghent (Belgium); Olomouc (Czech Republic); Aarhus (Denmark); Christchurch, North Shore, Waitakere, and Wellington (New Zealand); Stoke-on-Trent (UK); and Seattle, WA and Baltimore, MD (USA). Three were in upper-middle-income countries: Curitiba (Brazil), Bogota (Colombia), and Cuernavaca (Mexico).

In each city, small administrative areas (such as census block groups in the USA) were selected by IPEN and participants were recruited from these areas. These administrative areas were chosen to maximise the within-city variability in socioeconomic status and walkability. Socioeconomic status at the area level was defined with relevant census data (eg, household income or educational attainment) and area level walkability was established by a composite index defined as the sum of the Z scores for net residential density, street intersection density, and mixed land use.⁴⁴ In each city, administrative areas were ranked according to their socioeconomic status and walkability index and classified into one of four groups: (1) low walkability and low socioeconomic status; (2) low walkability and high socioeconomic status; (3) high walkability and low socioeconomic status; (4) and high walkability and high socioeconomic status. Depending on the participating cities, high and low groups were defined by median splits or by being in the top and bottom four deciles of administrative areas. Approximately equal numbers of areas were selected from each of the four groups. Further details about the area selection method of the IPEN Adult study are available.^{40,45}

Adults residing in the selected areas were contacted by IPEN and invited to complete a survey on their sociodemographic characteristics and physical activity. Study dates ranged from 2002 to 2011 across countries, with participants being recruited across seasons in each city to control for seasonal effects on physical activity. Data collection was dependent on local funding and, therefore, started in different years across countries. City-specific data collection periods ranged from 1 year to 3 years.⁴⁰ Each country obtained ethics approval from local institutions, and all participants provided written informed consent before participating. Kerr and colleagues⁴⁰ provide further details on participant recruitment and study procedures. Characteristics of participants were sorted by city and country income

groups (table 1). Samples from upper-middle-income countries tended to have a lower percentage of participants with higher education than those from high-income countries. The distributions of other sociodemographic characteristics across the two country-income groups were similar.

Exposure and outcome measures

Within IPEN, country sites used geographical information systems (GIS) software to measure urban design and transport features in participants' neighbourhoods related to walking. A neighbourhood was defined as the area reachable by the street network within 1 km of a participant's home, which is considered a walkable distance and is aligned with the concepts of 20-min neighbourhoods and 15-min cities.^{45–47} Measures included population density (people per km²), street intersection density (intersections per km²), and public transport density (public transport stops per km²). Street network distance (m) to the nearest transport stop and park were also measured. A manual of GIS variables that provided definitions and procedures to reduce measurement error and maximise comparability was shared with sites. Geographic information systems variable development and the comparability evaluations have been described in detail.⁴⁵ The appendix provides definitions of the urban design and transport measures used (p 1) and a summary of the GIS variable development and comparability evaluation (p 2).

See Online for appendix

Walking for transport and walking for recreation were measured by IPEN using the self-administered International Physical Activity Questionnaire-long form (IPAQ-LF), which has been extensively validated in 12 countries.⁴⁸ The form assesses the frequency and duration of physical activity across four domains. In this study, we used IPAQ-LF items to separately assess walking for transport and walking for recreation. Participants were asked to report how many days in the last week on which they walked for at least 10 min to get from place to place (transport) and for recreation, and the number of minutes usually spent on these activities each day. Weekly minutes of walking for transport and recreation were combined to obtain total walking. For this study, two measures were derived: any walking for transport during the last week that lasted at least 10 min (no vs yes); and at least 150 min of total walking during the last week (no vs yes). The total walking measure reflects the current WHO physical activity guidelines for adults.⁴

Determining thresholds

The study included the following covariates: age, sex, educational attainment (college graduate vs not), marital status (married or living with a partner vs all other), employment status (not employed vs employed), city or region and area-level socioeconomic status (low vs high).

Generalised additive mixed models (GAMMs) with binomial variance and logit link functions accounting for

	High-income countries										Upper-middle-income countries				
	All cities	Adelaide, SA, Australia	Ghent, Belgium	Olomouc, Czech Republic	Aarhus, Denmark	North Shore, New Zealand	Waitakere, New Zealand	Wellington, New Zealand	Christchurch, New Zealand	Stoke-on-Trent, UK	Seattle, WA, USA	Baltimore, MD, USA	Curitiba, Brazil	Bogota, Colombia	Cuernavaca, Mexico
Sample size	11 615	2407	1142	263	585	489	502	493	481	810	902	691	958	611	
Age, years	42 (13)	44 (12)	43 (13)	38 (15)	39 (14)	41 (12)	41 (12)	39 (13)	42 (13)	43 (13)	44 (11)	41 (13)	40 (14)	42 (13)	
Female	6586 (56.7%)	1540 (64.0%)	596 (52.2%)	172 (65.4%)	333 (56.9%)	315 (64.4%)	307 (61.2%)	252 (51.1%)	267 (55.5%)	452 (55.8%)	469 (52.0%)	365 (52.8%)	610 (63.7%)	329 (53.8%)	
Male	5029 (43.3%)	867 (36.0%)	546 (47.8%)	91 (34.6%)	252 (43.1%)	174 (35.6%)	195 (38.8%)	241 (48.9%)	214 (44.5%)	358 (44.2%)	433 (48.0%)	326 (47.2%)	348 (36.3%)	282 (46.2%)	
College education	5143 (44.3%)	1140 (47.4%)	696 (60.9%)	89 (33.8%)	284 (48.5%)	190 (38.9%)	154 (30.7%)	257 (52.1%)	157 (32.6%)	114 (14.1%)	609 (67.5%)	268 (38.8%)	214 (22.3%)	162 (26.5%)	
Employed	8755 (75.4%)	1739 (72.2%)	914 (80.0%)	200 (76.1%)	440 (75.2%)	383 (78.3%)	420 (83.7%)	427 (86.6%)	386 (80.2%)	531 (65.6%)	745 (82.6%)	535 (77.4%)	554 (57.8%)	440 (72.0%)	
Married or living with partner	7044 (60.6%)	1358 (56.4%)	841 (73.6%)	153 (58.2%)	386 (66.0%)	346 (70.8%)	373 (74.3%)	279 (56.6%)	269 (55.9%)	369 (45.6%)	546 (60.5%)	402 (58.2%)	512 (53.4%)	401 (65.6%)	
Low area-level SES	5643 (48.6%)	1128 (46.9%)	563 (49.3%)	109 (41.4%)	254 (43.4%)	164 (33.5%)	295 (58.8%)	248 (50.3%)	236 (49.1%)	375 (46.3%)	426 (47.2%)	345 (49.9%)	571 (59.6%)	304 (49.8%)	
Walking outcomes assessed in previous week by IPAQ-LF															
Any walking for transport	8411 (72.4%)	1837 (76.3%)	595 (52.1%)	225 (85.6%)	466 (79.7%)	318 (65.0%)	312 (62.2%)	420 (85.2%)	269 (55.9%)	530 (65.4%)	614 (68.1%)	534 (77.3%)	865 (90.3%)	552 (90.3%)	
≥150 min total walking	5859 (50.4%)	1333 (55.4%)	405 (35.5%)	219 (83.3%)	371 (63.4%)	186 (38.0%)	162 (32.3%)	300 (60.9%)	179 (37.2%)	408 (50.4%)	457 (50.7%)	284 (41.1%)	569 (59.4%)	321 (52.5%)	

Data are mean (SD) or n (%), unless otherwise indicated. SES=socioeconomic status. IPAQ-LF=International Physical Activity Questionnaire-Long Form.

Table 1: Descriptive statistics of sample sociodemographic characteristics and walking outcomes by city and country income groups

spatial correlation at the administrative area level were used to estimate the relationships of urban design and transport measures with the two binary walking outcomes (any walking for transport and ≥ 150 weekly min of total walking). GAMMs allow estimation of complex curvilinear relationships and can handle data with various distributional assumptions.⁴⁹ Because the study sampling strategy resulted in several urban design and transport measures being substantially correlated and real-world changes in these features are interdependent (eg, increases in public transport density need to be justified by demand), separate covariate-adjusted GAMMs were estimated for each urban design and transport variable and walking outcome relationship. The curvilinearity of associations was established by comparing Akaike information criterion values of models with linear and curvilinear terms of a specific urban design or transport variable. Models with curvilinear terms yielding Akaike information criterion values that were 5 units smaller than models with linear terms were deemed to provide sufficient evidence of curvilinearity.⁵⁰ Graphs were generated to depict relationships. To assess whether relationships varied by participants' sex and age, and by city, separate GAMMs were run with appropriate interaction terms added to the models.

Simulation with a Metropolis Hasting sampler was used to determine the threshold values (and their 95% CIs) of urban design and transport features associated with the two physical activity criteria: at least 80% probability of engaging in any walking for transport (here corresponding to a $\geq 10\%$ increase in prevalence), and the WHO target of at least 15% relative reduction in insufficient physical activity through total walking. The total walking target was defined as the percentage of the sample who would meet the WHO physical activity guidelines through total walking if there was a 15% relative reduction in the observed prevalence of those not meeting the guidelines. Threshold values and their 95% CIs were included in graphs depicting relationships. Further details on statistical analyses are provided in the appendix (pp 3–4), including the rationale for defining at least a 15% reduction in prevalence of not meeting the WHO physical activity guidelines on the basis of the observed sample prevalence.

Walking, urban design, and transport outcomes

In the 14 cities and country-income groups, 72.4% of the sample walked for transport, and 50.4% met WHO physical activity guidelines of at least 150 weekly min through total walking (table 1). The highest percentages of any walking for transport were observed in two samples from cities in upper-middle-income countries—Bogota and Cuernavaca—which also had the highest average intersection densities and were among the highest population densities (table 2). In four cities (Olomouc, Wellington, Bogota, and Cuernavaca) more

	Population density (people per km ²)		Intersection density (intersections per km ²)		Public transport density (stops per km ²)		Street network distance to nearest public transport stop (m)		Street network distance to nearest public park (m)	
	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
All cities	4568 (4097)	3072 (1953–5590)	81 (61)	69 (43–94)	15.7 (13)	14.5 (5.9–22.7)	475 (756)	243 (125–445)	482 (620)	307 (133–586)
High-income countries										
Adelaide, SA, Australia	1847 (698)	1835 (1343–2358)	65 (25)	67 (50–78)
Ghent, Belgium	5754 (4984)	4155 (980–9835)	84 (62)	73 (36–92)	9.4 (6)	7.8 (4.0–15.4)	314 (279)	256 (144–360)	829 (1180)	360 (137–772)
Olomouc, Czech Republic	4775 (2639)	4878 (2266–6640)	66 (19)	67 (52–79)	13.6 (6)	14.5 (9.5–17.7)	264 (175)	232 (153–365)	640 (493)	507 (323–791)
Aarhus, Denmark	8025 (6035)	6069 (2327–13402)	83 (22)	88 (72–98)	9.4 (5)	9.4 (5.6–13.0)	304 (230)	234 (146–393)	387 (376)	300 (170–492)
North Shore, New Zealand	2928 (713)	3049 (2785–3276)	26 (7)	26 (22–31)	18.6 (7)	19.7 (13.7–24.3)	251 (211)	199 (99–345)	239 (195)	190 (81–363)
Waitakere, New Zealand	2246 (706)	2366 (1920–2692)	28 (9)	28 (25–31)	9.6 (7)	7.4 (4.7–13.5)	333 (261)	292 (135–458)	458 (356)	411 (147–679)
Wellington, New Zealand	4030 (1521)	3336 (2954–5285)	44 (16)	44 (35–54)	16.6 (8)	15.3 (11.9–21.6)	224 (291)	149 (61–296)	350 (304)	317 (128–507)
Christchurch, New Zealand	3118 (684)	2901 (2651–3335)	35 (6)	36 (33–40)	16.3 (9)	16.5 (9.8–20.2)	294 (240)	238 (104–411)	333 (242)	294 (149–448)
Stoke-on-Trent, UK	4509 (1201)	4718 (3572–5329)	100 (34)	93 (76–123)	25.7 (8)	25.5 (19.3–31.5)	200 (133)	172 (101–273)	359 (279)	275 (157–488)
Seattle, WA, USA	3630 (4045)	2410 (1775–3733)	71 (23)	71 (56–85)	16 (10)	15.7 (9.0–22.8)	375 (430)	221 (127–447)	471 (369)	388 (215–610)
Baltimore, MD, USA	3271 (2194)	2561 (1746–4757)	55 (28)	53 (38–67)	17 (14)	15.7 (7.6–24.7)	629 (1002)	236 (116–538)	655 (634)	447 (246–810)
Upper middle-income countries										
Curitiba, Brazil	7897 (3208)	7381 (5448–9631)	76 (17)	71 (64–83)	25.9 (7)	24.9 (20.6–29.5)	185 (117)	164 (94–253)	356 (277)	292 (124–557)
Bogota, Colombia	10270 (5585)	9461 (6004–15168)	206 (96)	192 (130–286)	2.1 (3)	1.2 (0.0–3.4)	1678 (1422)	1150 (506–3306)	91 (74)	65 (35–138)
Cuernavaca, Mexico	5710 (2280)	5304 (4390–6615)	144 (46)	134 (111–158)	30.3 (25)	26.7 (12.2–40.5)	454 (607)	214 (97–522)	972 (857)	757 (299–1275)

Table 2: Descriptive statistics of urban design and transport measures

than 80% of the sample walked for transport, one of the physical activity criteria we used to define thresholds of urban design and transport features (table 1). The second criterion was a 15% relative reduction in insufficient physical activity through walking. With 50.4% of the sample meeting WHO physical activity guidelines through walking, a 15% reduction in insufficient physical activity translates to 57.9% of the sample meeting guidelines through walking. The samples from four cities met this physical activity criterion: Olomouc, Aarhus (Denmark), Wellington, and Bogota (table 1).

Thresholds

Population and intersection densities were curvilinearly related to both walking outcomes in an inverted-U manner ($p < 0.0001$), although confidence intervals at the higher end of the measures' range were large, due to the few observations (figures 1 and 2). We estimated that population densities of at least 5665 people per km² would be associated with a minimum 80% probability of walking for transport and 6491 people per km² would be associated with minimum 58% probability of accumulating at least 150 weekly min of total walking.

Only 24.2% of the total IPEN sample resided in neighbourhoods with optimal ranges of population density for transport and only 19.7% resided in neighbourhoods with optimal ranges of population density for total walking (table 3). Large between-city differences were observed against these thresholds, with samples from European cities generally performing better than those from Australasian and North American cities, and samples from cities in Latin American upper-middle-income countries performing better than those in high-income countries.

Similar between-city differences were observed for intersection density. Samples from two Latin American cities (Cuernavaca and Bogota) and Stoke-on-Trent (UK) had the highest percentage of participants living in neighbourhoods reaching the intersection density thresholds associated with at least 80% probability of walking for transport (98 intersections per km²) and a minimum 58% probability of accumulating at least 150 weekly min of total walking (122 intersections per km²; figures 1B, 2B).

An inverted-U relationship was observed between public transport density and the probability of walking

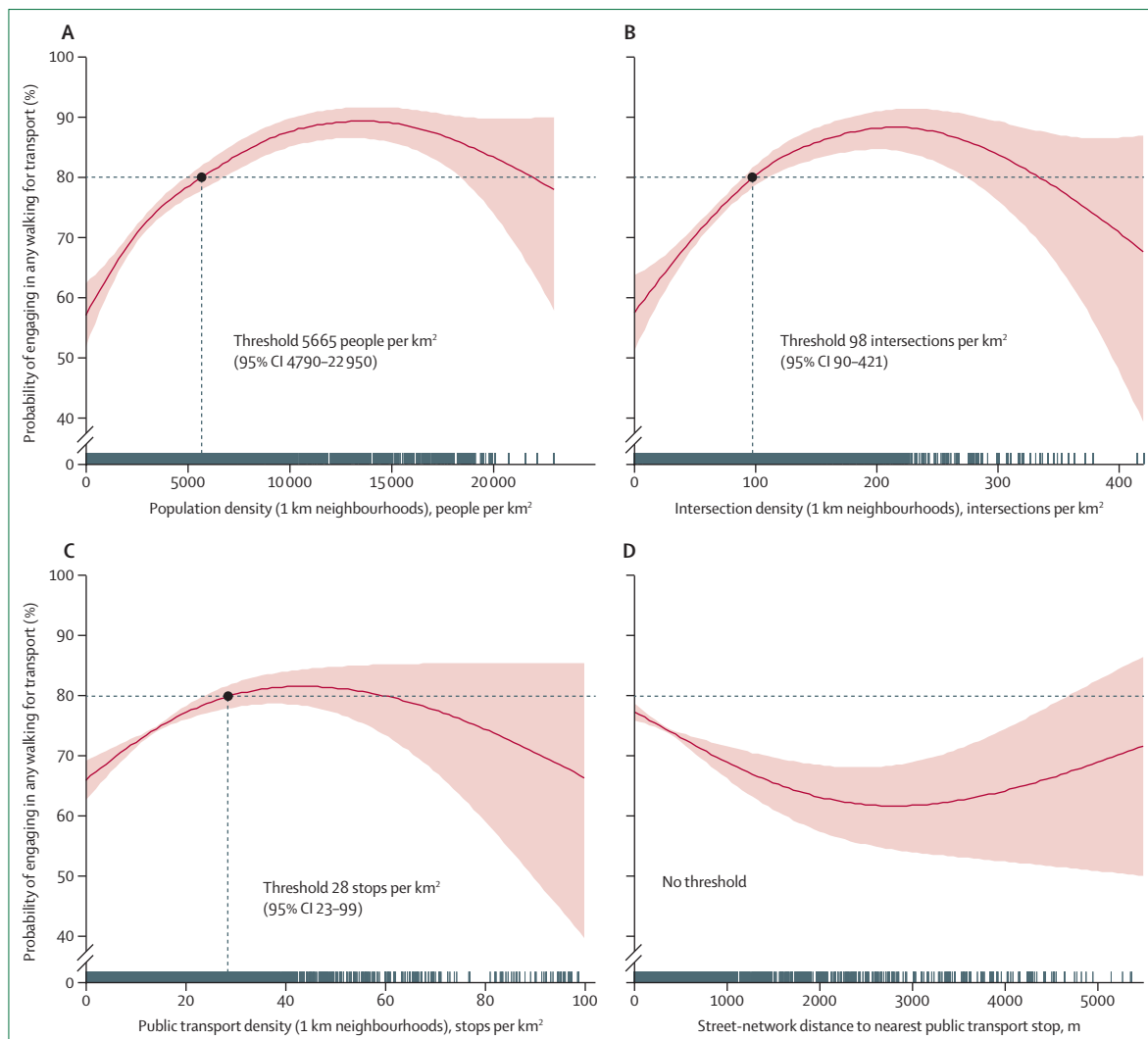


Figure 1: Relationships between urban design and transport measures, and the probability of any walking

Dotted vertical lines show thresholds associated with at least 80% probability of any walking for transport (dotted horizontal lines). Pink shading shows 95% CIs. A=population density. B=intersection density. C=public transport density. D=distance to nearest public transport stop.

for transport ($p < 0.0001$; figure 1C), with a threshold value of at least 28 stops per km² associated with a minimum 80% probability of walking for transport. Again, the samples from two Latin American cities (Cuernavaca and Curitiba) and a European city (Stoke-on-Trent) had the highest percentage of participants reaching this threshold. The association between public transport density and the likelihood of accumulating at least 150 weekly min of total walking was weaker (OR 1.005; 95% CI 0.999–1.011; $p = 0.0683$). Distance to the nearest public transport stop was also curvilinearly related to walking for transport ($p = 0.0003$). However, none of the values for distance to nearest public transport stop were associated with meeting a minimum 80% probability of walking for transport (figure 1D).

Distance to the nearest public park was linearly negatively related to the likelihood of engaging in any

walking for transport (OR 0.973; 95% CI 0.961–0.985; $p = 0.0007$) and accumulating at least 150 min weekly of total walking (0.983; 0.972–0.993; $p = 0.0013$). However, none of the distance values were associated with a minimum 80% probability of walking for transport (appendix p 6) or a minimum 58% probability of accumulating at least 150 weekly min of total walking (appendix p 7). None of these associations varied by city, age, or sex (appendix p 5).

Certain areas in some cities exceeded the optimal thresholds for population, intersection, and public transport densities, beyond which we observed probabilities of walking for transport lower than 80% or probabilities of accumulating at least 150 min weekly of total walking lower than 58% (see differences between threshold and optimal range percentages in table 3). This outcome was evident in the samples from Bogota,

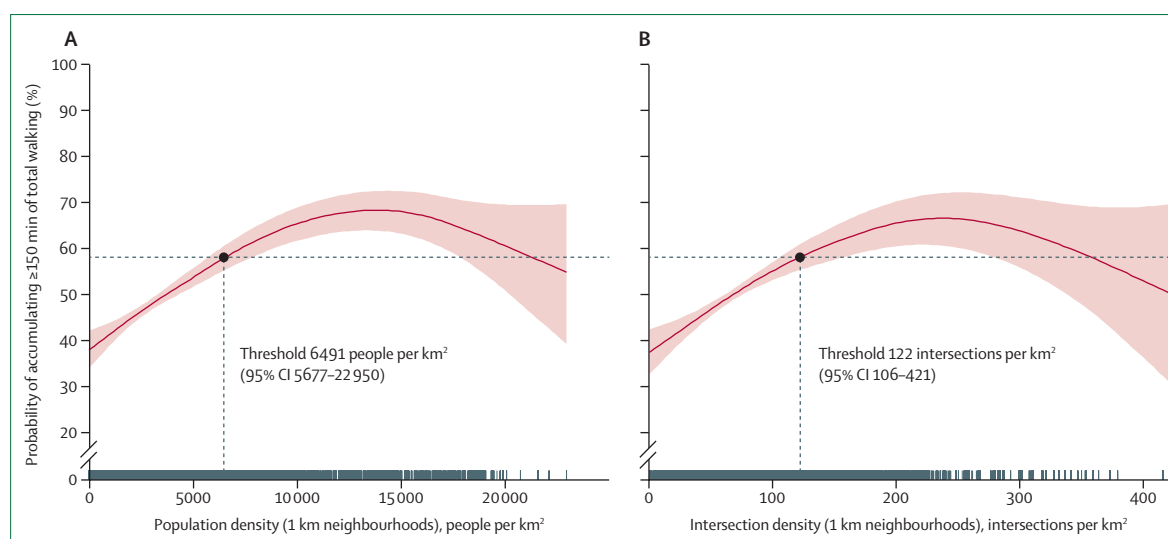


Figure 2: Relationships between urban design measures and the probability of ≥ 150 minutes of total walking per week

Dotted vertical lines show the thresholds associated with at least 58% probability of at least 150 min of total walking per week (dotted horizontal lines). Pink shading shows 95% CIs. A=population density. B=intersection density.

where approximately 10% of the participants resided in neighbourhoods exceeding the optimal range of intersection density, and in Cuernavaca, where 13% of participants resided in neighbourhoods exceeding the optimal range of public transport density.

Discussion

To inform the development of measurable urban planning and transport policy standards and targets for healthy and sustainable cities, we estimated the associations between key urban design and transport features and two walking outcomes—walking for transport and meeting WHO physical activity guidelines via walking—from data for 11 615 adults from 14 cities across seven high-income and three upper-middle-income countries. We then identified the thresholds of urban design and transport features associated with specific physical activity criteria. Our findings suggest that urban neighbourhoods with at least around 5700 people per km², 100 intersections per km², and 25 public transport stops per km² would yield optimal outcomes for both walking for transport and meeting WHO physical activity guidelines through walking. No thresholds were identified for distances to the nearest public transport stop and public park. However, shorter distances to both types of destinations appeared to facilitate more walking. We found no evidence for differences in associations by sex, age, or city, which reflects previous findings from the same IPEN Adult cohort in relation to objectively measured physical activity,³¹ and supports the generalisability of findings to various sociodemographic groups and the diverse global cities studied.

Although most research on urban design and transport correlates of physical activity assume or report linear associations,^{23,26,28} we found evidence of curvilinearity in

60% of the estimated associations. This outcome could be due to the increased variability of urban design and transport features resulting from the use of data for several diverse cities from many countries, as opposed to the use of data from a single city or country.^{40,52} Although the findings suggest that many of the cities studied had densities below the optimal range for walking and would benefit from densification, there seem to be upper thresholds of densities beyond which gains in walking are no longer observed. Of note, evidence from ultra-dense cities in Asia, in particular China, where 27 000 people per km² is considered low density, reveals negative relationships between population density and walking by adults,^{53,54} with similar findings observed in Mexico.⁵⁵ The maximum value of population density in our study was 22 950 people per km², because ultra-dense cities were not included. Therefore, we were unable to characterise the shape of the relationship between ultra-high density and walking. However, consistent with previous evidence (from China, India, and Mexico), our findings suggest negative associations between population density and walking in areas exceeding 14 000–14 500 people per km² (figures 1A, 2A). High population densities typically come with more proximate diverse destinations and regular public transport services, which might reduce the distances walked.

Applications and interpretation of the derived thresholds

Empirically derived thresholds can be used as city planning policy standards and serve as benchmarks against which cities can be evaluated and monitored. As a starting point, the thresholds for this subset of urban design and transport features can be used to identify which parts of cities are appropriately designed to

contribute positively to achieving health and sustainability goals. In the first paper in this Series, Lowe and colleagues³² found that many city planning policies, particularly those in middle-income countries, did not have evidence-informed measurable standards and targets. In the third paper, Boeing and colleagues⁵⁶ show how spatial indicators with health-enhancing thresholds can identify spatial inequities within and between cities in diverse lower-middle-income countries and high-income countries.

Quantitative thresholds similar to those determined in this study are essential for the formulation of measurable standards and targets. These thresholds can be used to evaluate whether current city planning policies take them into consideration and to revise city planning policies to incorporate standards and targets so that they are more likely to contribute to health and sustainability goals. In a post-COVID world where governments are promising to build back better through 15-min cities,^{46,47} thresholds for built environment interventions could be very useful. Optimal thresholds for the broad range of urban design and transport features that create healthy and sustainable cities for all (see our conceptual framework in paper four in this Series by Giles-Corti and colleagues)⁵⁷ need to be established to avoid counterproductive efforts. For example, walkable, high-density neighbourhoods could attract increased traffic and expose residents to air and noise pollution and traffic-related injuries and mortality.^{10,58–60} Thresholds focused on walking and derived from healthy adult samples might have unintended consequences for children or people with mobility problems and those using other active modes of transport (eg, cycling, skating, or wheelchairs). City leaders can use evidence-informed thresholds to evaluate and improve their own cities, and external national and international organisations can use them to monitor many cities' progress towards meeting UN Sustainable Development Goals and other recommendations.

The present analyses showed that several cities in the IPEN Adult study included neighbourhoods that met the thresholds for certain urban design and transport features, and that the two walking criteria used to define the thresholds might be feasible to achieve. However, we observed pronounced differences between cities, countries, and regions in the sample prevalence of meeting urban design and transport feature thresholds, even though associations were generalisable across cities. Our results should not preclude decision makers from carefully considering the nuances of their local context when designing and planning cities for health and sustainability. For almost all city-specific samples, the percentage of participation in walking for transport was markedly higher than the percentage of participants with neighbourhood urban design and transport features meeting the established thresholds. This disparity implies that additional factors beyond the examined

urban design and transport features influence walking behaviour in cities.^{61,62} Some of these were accounted for in our analysis, such as educational attainment (usually considered a good proxy for socioeconomic status): a US study found different thresholds across income levels.³⁹ However, other factors that vary across cities, such as local governance, city planning policies,^{32,62} motor vehicle ownership,⁵¹ poverty, crime,⁶³ and social norms,⁶⁴ were not accounted for in this study. Optimal thresholds and appropriate targets could depend on other urban design features, cultural norms and attitudes, lifestyle choices, and sociodemographic factors.

Motor-vehicle ownership is another important factor for understanding active travel behaviour. In places where a large proportion of the population cannot afford to own a private motor vehicle, most physical activity for transport decisions are based on necessity rather than choice.^{65,66} Our findings from Bogota and Cuernavaca support this hypothesis, with most (>90%) participants from these cities walking for transport, although few people lived in areas with optimal ranges of urban design features (about 40%) for walking for transport.⁶⁷ The difference between the percentage of participants walking for transport and those residing in neighbourhoods at or above the thresholds of urban design and transport features was particularly large in cities with average population densities less than 5000 people per km²—eg, Adelaide, North Shore, and Seattle. This finding might be due to the sampling strategy adopted by the IPEN Adult study, which required that 50% of the participants be recruited from the most walkable neighbourhoods in each city;⁴⁰ consequently, these participants had good access to amenities for daily living,⁶³ which is the most salient urban design feature for walking and was not measured by IPEN Adult.^{23,31,56,62}

Another important consideration when using our results for guiding city planning efforts is the shape of the associations we observed. Most participants in our study lived in areas likely to benefit from increases in population, intersection, and public transport densities. However, in Bogota and Cuernavaca, there were notable differences between the percentage of participants meeting thresholds for some urban design and transport features, and the percentage within an optimal range for the same feature. This observation suggests that some participants lived in areas where these urban design features could be too high to achieve the best possible walking outcomes. Therefore, a more-is-better approach might not always be the most appropriate message for every city, or for all areas of a city. This study could not accurately characterise the shape of relationships at high densities, which limited our ability to draw strong conclusions about upper limits of optimal ranges of features. Nevertheless, our results are consistent with those elsewhere, and serve as a warning that there are limits to the degree of health-supportive density. In the face of rapid urbanisation, this hypothesis requires further exploration.

Strengths and limitations

This study had several strengths, one of which was being informed by comparable data from various cities across culturally and geographically diverse countries. Another strength was the stratified sampling strategy. Although not suited to estimating the population-level prevalence of walking and meeting optimal thresholds of urban design and transport features, the sample maximised variability in important urban design and transport features (eg, population, intersection, and public transport densities) and facilitated the characterisation of the shape of relationships. Study limitations included the exclusive reliance on self-reports to measure walking; the few environmental features that could be examined; the absence of data from low-income countries and information on socioeconomic characteristics that could explain the observed between-city differences in environmental features and walking; poor representation of middle-income countries and ultra-dense cities; few data from small and middle-size cities (where a third of the world's urban population lives and where resources and capacity for city design and planning are limited);⁶⁸ the cross-sectional nature of the study; and insufficient adjustment for residential self-selection precluding the estimation of causal effects,⁶⁹ climatic conditions, and car ownership.^{61,63} However, the aim of this study was not to estimate causal effects but rather the thresholds of environmental features associated with specific physical activity criteria regardless of the underlying mechanisms (environmental influences or residential self-selection) as this information is important to urban planners and policy makers. By correlating features of the residential neighbourhood with both walking for transport and total walking (in and outside the neighbourhood), our analysis might have overestimated the effects of the residential environment.^{70,71} We should consider how the selective built environment sampling method used in this study might affect the generalisability of the results for promoting policy thresholds for broad global application. Finally, as population density is measured in various ways (eg, people *vs* dwellings or density based on total area *vs* residential-use area only), thresholds identified in this study need to be adjusted if other metrics are used.

Conclusion

We found that residing in neighbourhoods exceeding around 5700 people per km², 100 intersections per km², and 25 public transport stops per km² was associated with meeting one or both policy-relevant physical activity criteria. The empirically derived thresholds for spatial urban design and transport features for walking presented in this study illustrate how research on urban environments and health can assist the development of evidence-based, measurable standards and targets for city planning policy. Although we believe that the derived thresholds reported here could be applied internationally, we do not consider them to be definitive or final. To

establish robust, universally applicable thresholds, further analyses of population-representative samples with a broader range of international cities of different sizes, including more low-income to middle-income countries with higher population densities, other geospatial features and metrics (eg, perceived environmental attributes and space syntax measures), and other behavioural and health outcomes, should be conducted. This requires large international, ideally longitudinal, studies with comparable measures and research protocols that enable pooled analyses. However, multicountry longitudinal or quasiexperimental studies that are capable of capturing a sufficiently large range of environmental changes to quantify international causal effect thresholds would be very challenging to do, if feasible at all. To meet UN Sustainable Development Goals that target inequalities, studies should also establish the appropriateness and validity of specific thresholds for different sexes, ages, and socioeconomic groups.^{72,73} As the evidence grows, it might be possible to reach a consensus on thresholds for each urban design and transport feature that summarises results based on several health outcomes. These findings need to be clearly communicated to policy makers, who could incorporate them into evidence-informed standards and targets for city planning policy, and thereby support the creation of healthy and sustainable urban environments.

Contributors

EC, JFS, DS, ML, EH, AVM, CH, DA, GB, and SL were part of the study executive team. EC, JFS, DS, ML, EH, AVM, CH, and BG-C contributed to conceptualisation and study design. EC contributed to study method, formal data analysis, and verification of data. EC, DS, CH and BG-C contributed to data visualisation. EC, JFS, DS, ML, EH, AVM, TLC, NO, DvD, CH, DA, and BG-C contributed to writing the original draft and reviewing and editing it. EC, JFS, DS, ML, EH, AVM, TLC, DvD, MAA, and BG-C contributed to data interpretation. MAA, LDF, RR, LC, KLC, RD, JD, OLS, GB, and SL contributed to reviewing the draft and editing for important intellectual content. BG-C led the study executive team. IPEN Adult study roles: EC, TLC, MAA, LDF, and KLC contributed to the method. EC, DS, TLC, NO, DvD, RR, LBC, RD, and OLS contributed to project coordination. ED, DS, EH, TLC, NO, DvD, MAA, LDF, RR, LBC, KLC, RD, JD, and OLS contributed to data collection. EC, DS, NO, LDF, and RR contributed to funding acquisition. JFS was the principal investigator and led international data coordination, study design, data collection and funding acquisition for international coordination. EH, TLC, MAA, LDF, KLC, and JD contributed to data coordination. TLC, MAA, and KLC contributed to data verification. NO contributed to study design. MAA, LDF, and JD contributed to data visualisation.

Declaration of interests

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