Cities 141 (2023) 104518

Contents lists available at ScienceDirect

Cities

journal homepage: www.elsevier.com/locate/cities

# How the perceived neighbourhood environment influences active living in older dwellers of an Asian ultra-dense metropolis

Ester Cerin [a,b,*], Casper J.P. Zhang [b], David W. Barnett [c], Ruby S.Y. Lee [d], Cindy H.P. Sit [e], Anthony Barnett [a]

[a] *Mary MacKillop Institute for Health Research, Australian Catholic University, Melbourne, Victoria, Australia*
[b] *School of Public Health, Li Ka Shing Faculty of Medicine, The University of Hong Kong, Hong Kong*
[c] *School of Behavioural and Health Sciences, Faculty of Health Sciences, Australian Catholic University, Melbourne, Victoria, Australia*
[d] *Elderly Health Service, Department of Health, The Government of Hong Kong Special Administrative Region, Hong Kong*
[e] *Department of Sports Science and Physical Education, Faculty of Education, The Chinese University of Hong Kong, Hong Kong*

ARTICLE INFO

*Keywords:*
Physical activity
Sedentary behaviour
Walkability
Accelerometers
Mediation
Older adults

ABSTRACT

The way older adults perceive their neighbourhood environment may determine their levels of physical activity. We examined the associations of perceived neighbourhood environmental attributes with accelerometry-assessed and self-reported physical activity and sedentary time in Hong Kong Chinese older adults. In doing so, we estimated the inter-relationships among perceived environmental attributes, the mediating role of physical activity in the environment-sedentary time nexus and the moderating role of sex. We used data from the Active Lifestyle and the Environment in Chinese Seniors (ALECS) project collected on older adults ($N = 909$; ≥65 years) living in neighbourhoods varying in walkability and socio-economic status (71 % response rate). Self-reported physical activity and perceived neighbourhood attributes were assessed with validated questionnaires. Accelerometer-based physical activity and sedentary time were collected in 402 participants. Older adults who perceived their neighbourhood to be walkable, safe, aesthetically pleasing and equipped with public sitting facilities engaged in more physical activity and less sedentary time. Curvilinear relations of perceived residential density and activity-friendly urban design features indicated that extreme levels of density may not be optimal for older adults to adopt an active lifestyle because they do not provide sufficient space for sitting facilities and greenery and do not result in better perceptions of neighbourhood walkability when compared to areas with moderate-to-high levels of density. Creative solutions for the incorporation of greenery and public places for sitting in megacities are needed.

## 1. Introduction

Research has long established that regular engagement in physical activity, particularly moderate-to-vigorous intensity physical activity (MVPA), is beneficial to older adults' health (Cunningham et al., 2020; Lee et al., 2012). In addition, a growing body of evidence suggests that time spent in sedentary activities (i.e., 'any waking behaviour characterized by an energy expenditure ≤1.5 metabolic equivalents (METs), while in a sitting, reclining or lying posture' (Tremblay et al., 2017)) is associated with increased all-cause mortality, and poorer cognitive (Steinberg et al., 2015) and cardiometabolic health in older adults (de Rezende et al., 2014; Steinberg et al., 2015). However, studies suggest that 40 %–80 % of older adults do not meet the physical activity guidelines for health and their physical activity levels decline over time (Sun et al., 2013). Hence, finding ways to promote active living (i.e., increase physical activity and reduce sedentary time) in older populations is a public health priority.

There is general consensus that neighbourhoods that are safe, aesthetically-pleasing, with good access to destinations and services and a mix of land-uses facilitate the accumulation of physical activity among older adults (Barnett et al., 2017; Cerin et al., 2017; Van Cauwenberg et al., 2018). The extent to which these neighbourhood characteristics influence sedentary time remains unclear due to the limited research on this issue. Considering older adults spend most of their day in their neighbourhood (Glass & Balfour, 2003) and the amount of sedentary time increases with age—sometimes up to 80 % of a waking day

* Corresponding author at: Mary MacKillop Institute for Health Research, Australian Catholic University, Melbourne, Victoria, Australia.
*E-mail addresses:* Ester.Cerin@acu.edu.au, ecerin@hku.hk (E. Cerin).

https://doi.org/10.1016/j.cities.2023.104518
Received 13 March 2023; Received in revised form 12 July 2023; Accepted 4 August 2023
Available online 10 August 2023

(Arnardottir et al., 2013; Davis et al., 2011; Evenson et al., 2012; Matthews et al., 2008) —research investigating sedentary time in relation to the aspects of the built (e.g., access to services), natural (e.g., access to blue and green spaces) and social (e.g., crime, crowdedness) neighbourhood environment is warranted.

The few studies that have investigated the potential effects of the neighbourhood environment on older adults' sedentary time reported mixed findings. Negative (Cerin et al., 2021; Cerin, Van Dyck, et al., 2020), null (Barnett et al., 2015; Cerin et al., 2016; Fleig et al., 2016; Oyeyemi et al., 2019) as well as positive (Cerin, Van Dyck, et al., 2020) associations between sedentary time and measures of neighbourhood green space (e.g., parks, presence of trees) have been reported. The same has been observed in relation to attributes of the built environment, such as residential density (Cerin et al., 2016; Cerin, Van Dyck, et al., 2020; Oyeyemi et al., 2019) and commercial services (Cerin et al., 2016; Fleig et al., 2016; Oyeyemi et al., 2019), the social environment, such as crime (Barnett et al., 2015; Fleig et al., 2016; Oyeyemi et al., 2019), and composite indices of neighbourhood walkability (Amagasa et al., 2019; Greenwood-Hickman et al., 2022; Oyeyemi et al., 2019). These conflicting findings could be due to methodological and/or contextual differences. For example, the three studies that examined the associations between neighbourhood walkability and sedentary time were conducted in three culturally and geographically diverse countries across three continents – namely, Japan (Asia) (Amagasa et al., 2019), Nigeria (Africa) (Oyeyemi et al., 2019) and the USA (North America) (Greenwood-Hickman et al., 2022). Moreover, while the Nigerian study employed self-report measures of the neighbourhood environment and sitting time (Oyeyemi et al., 2019), the US study used a self-report measure of the environment and objective, inclinometer-based sitting time (Greenwood-Hickman et al., 2022), and the Japanese study employed objective, Geographic Information Systems (GIS)-based measures of the environment and an accelerometer-based measure of sedentary time (Amagasa et al., 2019). To better understand how the neighbourhood environment may affect older adults' active living, more studies in different geographical and cultural contexts and using different exposure and outcome measures are needed.

Another shortcoming of current research on the neighbourhood environment and older adults' active living pertains to physical activity and sedentary time being considered independent outcomes and, consequently, being analysed separately (Amagasa et al., 2019; Fleig et al., 2016; Greenwood-Hickman et al., 2022; Oyeyemi et al., 2019). Yet, as evidenced in two recent studies (Cerin et al., 2021; Cerin, Van Dyck, et al., 2020), it is plausible to assume that environments that promote or facilitate engagement in physical activity will, to a certain extent, result in less time being spent on sedentary activities due to physical activity displacing some of that time. Examining the mediating role of physical activity in the associations between the neighbourhood environment and sedentary time is important for two reasons. First, the statistical power of mediation analyses to detect weak associations between exposures and distal outcomes (here, sedentary time) is much greater than that of analyses of associations representing the total effects of the exposures on the same outcomes (O'Rourke & MacKinnon, 2015). Second, environmental attributes may contribute to the substitution of sedentary time with MVPA (e.g., walking) and simultaneously displace some lighter intensity activity with sedentary activities (Barnett et al., 2015). In this case, a positive association between an environmental feature and sedentary time would be detected only after adjusting for MVPA.

Furthermore, in formulating regression models of total and independent effects of urban design features on active living, very few studies have considered how key urban design features are causally interlinked (Cerin et al., 2021; Cerin, Barnett, et al., 2020; Cerin, Van Dyck, et al., 2020). In addition to gains in statistical power (O'Rourke & MacKinnon, 2015), the explicit modelling of potential causal links between environmental features can help to unravel the positive and negative sequel of urban densification. For example, higher levels of residential density usually result in better access to a wide range of amenities which may encourage active transport (Cerin, Barnett, et al., 2020; Giles-Corti et al., 2022) and reduce leisure-time sitting (Cerin et al., 2021). At the same time, densification may lead to reductions in green space and aesthetics, and increases in traffic load (Cerin et al., 2021; Cerin, Barnett, et al., 2022; Frank et al., 2003), which may negatively impact on leisure-time physical activity (Van Cauwenberg et al., 2018) and increase sitting (Cerin et al., 2021). Also, some types of destinations, such as places of worship or passive entertainment, have been associated with more walking for transport within the neighbourhood (Cerin et al., 2013) but also with more non-transport sitting (Barnett et al., 2015). It is important to identify these potential competing pathways to more effectively develop interventions that enhance the beneficial, and minimise the harmful, aspects of urbanisation and densification (Cerin, Barnett, et al., 2020).

To the authors' knowledge, only two studies on the neighbourhood environment and older adults' physical activity and sedentary time have considered the interrelationships of environmental attributes and the mediating role of physical activity (Cerin et al., 2021; Cerin, Van Dyck, et al., 2020). Both studies focused on objectively-assessed rather than perceived features of the environment, such as dwelling density and percentage of commercial land. Understanding how perceived attributes of the environment are interrelated and potentially affect active living is also theoretically and practically important. Because people's perceptions of their neighbourhood result from the interaction between the objective environment and their psychosocial and physical characteristics, they are more closely related to their behaviour (Barnett et al., 2017; Sallis et al., 2006). Moreover, perceived neighbourhood environmental attributes typically refer to a time-based definition of neighbourhood (e.g., 15–20-min walk from home) (Brownson et al., 2009), which may be more appropriate for older people than distance-based definitions (e.g., objective 800-m home-centred buffers) due to large interindividual differences in mobility and physical capacity (Boakye-Dankwa et al., 2019; Cerin et al., 2017; Satariano et al., 2012).

To address the above-mentioned research gaps, this study aimed to examine the strength and shape of associations of perceived neighbourhood environmental attributes with accelerometry-assessed and self-reported physical activity and sedentary time in older adults. In doing so, we estimated the inter-relationships among perceived environmental attributes, the mediating role of physical activity in the environment-sitting time nexus and the moderating role of sex. The latter was investigated because between-sex differences in physical and psychosocial characteristics may result in different perceptions of the environment and their influence on behaviours (Sallis et al., 2006). Fig. 1 summarises the hypothesised relationships based on the literature reviewed above (see Supplementary Material for detailed hypotheses).

Our study focuses on older urban dwellers of an ultra-dense Chinese metropolis, Hong Kong. The need for examining this population and geographical context is based on multiple reasons. First, China houses the largest proportion of older adults in the world (United Nations, Department of Economic and Social Affairs, Population Division, 2013), nearly a third of whom reside in ultra-dense metropolises similar to Hong Kong (World Bank Group, 2021). Second, urbanisation and the percentage of older adults living in cities are increasing worldwide, with Asia leading the race (United Nations, Department of Economic and Social Affairs, Population Division, 2019). Third, Hong Kong boasts much higher levels of variability in residential density and accompanying urban design features (e.g., access to services) than the typical Australian, American and European cities (Adams et al., 2014), making it the ideal context for examining dose-response relations between the neighbourhood environment, physical activity and sedentary time.

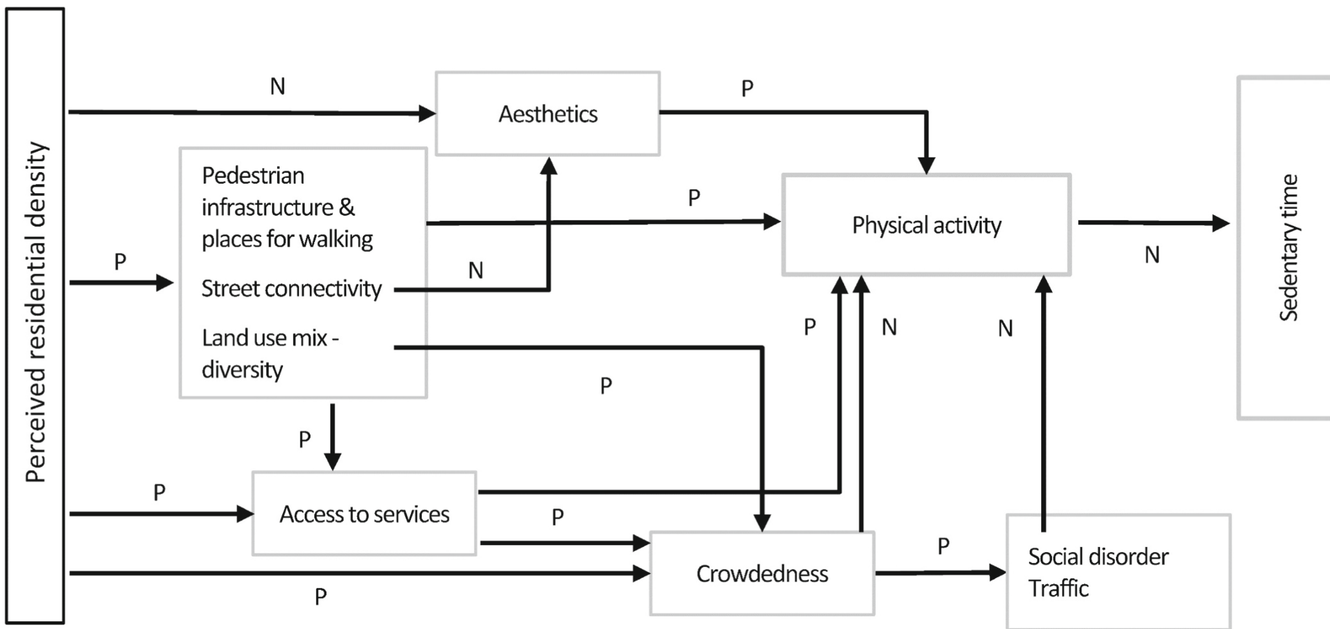


**Fig. 1.** Conceptual model of the effects of perceived neighbourhood environmental attributes on physical activity and sedentary time. N and P indicate hypothesised negative and positive relationships, respectively.

## 2. Materials and methods

### 2.1. Study design and participant recruitment

The Active Lifestyle and the Environment in Chinese Seniors (ALECS) study is an observational, cross-sectional study examining the associations of attributes of the neighbourhood built and social environment, and psychosocial factors with physical activity, quality of life and depressive symptoms in Hong Kong older adults aged ≥65 years (Cerin et al., 2016). Ethics approval for the ALECS study was obtained from The University of Hong Kong's Human Research Ethics Committee for Non-Clinical Faculties (Project ID: EA270211) and the Department of Health (Hong Kong Special Administrative Region, Hong Kong SAR).

As detailed in the published protocol paper (Cerin et al., 2016), a two-stage stratified sampling strategy was adopted whereby 909 Hong Kong older adults were recruited from urban areas in Hong Kong stratified by walkability (a composite index of objectively measured dwelling and intersection densities and land use mix) and socio-economic status (median household income) into high walkable/high socio-economic status, high walkable/low socio-economic status, low walkable/high socio-economic status, and low walkable/low socio-economic status. Tertiary Planning Units (TPUs) - the smallest administrative units with publicly available census data in Hong Kong, falling within the first and last four deciles of a stratification dimension were, respectively, classified as low and high on that dimension. The stratified sampling strategy was chosen to maximise the variability in environmental exposures (aspects of walkability) and outcomes (physical activity) to assist estimation of curvilinear relationships (if any). Of note is that the range of the walkability score of TPUs excluded from the study was −0.97 to 0.06 (minimal), while that of the selected TPUs was −1.97 to 5.96 (large). A hundred and twenty-four TPUs were randomly selected to represent each of the four strata (31 TPUs per stratum). All TPUs were represented in the final sample. Approximately 7–8 older adults were recruited from each TPU and ~ 45 % of participants ($n$ = 416) were randomly selected to wear an accelerometer to objectively assess MVPA and sedentary time.

Due to privacy ordinance restrictions (Cerin et al., 2016), it was not possible to obtain a comprehensive sampling frame for participant recruitment across Hong Kong neighbourhoods. Hence, 70 % of participants were recruited in person from eight out of 18 Elderly Health Centres established by the Department of Health of the Government of Hong Kong SAR to provide comprehensive primary care services for Hong Kong residents aged ≥65 years; and 30 % were recruited from elderly community centres and housing estates with the help of staff from the Sao Po Centre on Ageing (The University of Hong Kong) with established community links. We recruited most of the sample through the Elderly Health Centres because of their members' willingness to take part in health-related studies endorsed by the Department of Health and the ability to have them pre-screen for eligibility by centre staff. Although members of these centres are representative of the general population of Hong Kong older adults in terms of age, socio-economic status and hospital utilisation (Schooling et al., 2006), they are more health conscious (Sun et al., 2012) and, hence, tend to lead an active lifestyle. To examine the possible biases associated with having participants from the health centres, we recruited nearly a third of sample from general senior community centres with no formal provision of health services. The response rate, representing the percentage of contacted eligible participants who consented to take part in the study, was 71 %. Eligibility criteria were being/having: ≥65 years old; Cantonese-speaking and able to communicate verbally; lived in one of the selected residential buildings for ≥6 months; able to walk unassisted for ≥10 m; and cognitively intact. A modest incentive and participation certificate were provided for completing the survey (HK$50) and 7-day accelerometer component (additional HK$50). All participants entered a draw to win one of the three gift certificates valued at HK$2000.

### 2.2. Measures

#### 2.2.1. Perceived neighbourhood environment (exposures)

Participant perceptions of the neighbourhood environment were assessed using the Neighbourhood Environment Walkability Scale for Chinese Seniors (NEWS-CS) (Cerin et al., 2010). Participants report information on their neighbourhood environment defined as an area within 10-to-15-min walking distance from their home. For this study, nine categories of environmental attributes depicted in Fig. 1 and detailed in the Supplementary Material (section S1) were assessed. They encompassed: (a) residential density (e.g., apartments with 13–20 stories); (b) street connectivity (e.g., short distance between intersections); (c) land use mix – diversity (e.g., pharmacy/drug store, gymnasium, public transit); (d) access to destinations and services (e.g., shops are within walking distance); (e) pedestrian infrastructure and places for walking, including physical environmental barriers to walking, infrastructure for walking (e.g., sidewalks/pavements), indoor places for walking (e.g., indoor, air-conditioned places for walking) and benches/sitting facilities; (f) aesthetics (e.g., many attractive natural sights); (g) crowdedness (e.g., crowded streets); (h) social disorder including crime and other signs of social disorder (e.g., many homeless people, drug addicts on the streets); and (i) traffic (e.g., heavy traffic along nearby streets). Residential density was assessed using six items rated on 5-point scale whereby ratings are weighted according to the average residential density that an item represents. The weighted ratings are then summed to create a perceived residential density score. Land-use mix – diversity consisted of 30 items assessing walking time to the nearest type of facility from home using a 5-point scale ranging from 1 to 5 min to 30+ minute walking distance. Items were reverse scored and the average score on all these items was computed to quantify land use mix –diversity. The items of the remaining subscales were rated on a 4-point Likert scale with anchors ranging from *strongly disagree* to *strongly agree*. Ratings on the items included in a specific subscale were reverse scored, if needed, and averaged.

#### 2.2.2. Physical activity and sedentary time (mediators and outcomes)

Self-reported weekly minutes of non-walking MVPA and sitting time were assessed using the Chinese version of the International Physical Activity Questionnaire (IPAQ-C) – Short (usual week) validated in this population (Deng et al., 2008). Weekly minutes of transport and recreational walking (in a usual week) were measured using the Neighbourhood Walking Questionnaire – Chinese version for Seniors (NWQ-CS), also adapted for, and validated in, Hong Kong older adults (Cerin et al., 2011). Participants reported weekly minutes of walking for transport and recreation undertaken within and outside the neighbourhood. For this study, weekly minutes of walking for different purposes and non-walking MVPA were summed and divided by seven (days) to provide an estimate of daily self-reported physical activity comparable to the objective, accelerometer-based measure of MVPA described below. The same was done for self-reported sitting time. While (total) self-reported daily physical activity was one of the primary outcomes, the three self-report measures of physical activity were secondary outcomes and examined in supplementary analyses to better understand the associations between the perceived environment, self-reported physical activity and self-reported sitting time (Table S4 and Fig. S9). A more detailed description of these measures is provided in the Supplementary Material (section S2).

Objective MVPA and sedentary time were assessed over seven consecutive days using the ActiGraph GT3X accelerometer worn above the right hip using an elastic belt. The ActiGraph has been validated for use among older adults and is among the most reliable and valid field measures of physical activity (Buman et al., 2010; Colbert et al., 2011). Data were collected at 60-s epochs using the Low Frequency Extension filter and non-wear periods were considered as >90 min of consecutive zero counts (Choi et al., 2012). Only vertical-axis data were analysed in the present study. Cut-point thresholds were used to determine the proportion of time spent in different intensities. Specifically, ≥1013 counts per minute (Barnett et al., 2016) were used to identify MVPA and < 25 counts per minute were used to identify sedentary time (Aguilar-Farías et al., 2014). Average daily minutes of accelerometer-assessed MVPA and sedentary time were the variables used in this study.

#### 2.2.3. Socio-demographic and health characteristics (participants' characteristics and covariates)

Interviewer-administered questionnaires provided data on age (in years), sex (female or male), educational attainment (up to primary schooling or at least secondary schooling), marital status (married or cohabiting, widowed or other), living arrangements (living alone or living with others) and household car ownership (yes or no). For participants recruited at the Elderly Health Centres, Elderly Health Centre medical staff collected data on the number of diagnosed medical conditions and, for those recruited from community centres, data were collected by researchers using the same clinical health-problems checklist with 23 chronic conditions. In this study, sex was treated as a covariate and moderator.

### 2.3. Data collection procedures

All questionnaires were interviewer-administered to 909 participants (average duration ~1.25 h). The subgroup of 416 participants randomly selected for the accelerometer component of the study were asked to wear the accelerometer during waking hours for 7 consecutive days and keep a log of wearing time. These participants received a daily phone call at a pre-determined time to motivate participation and verify compliance. Participants with fewer than five valid (i.e., ≥10 h per day) days (including ≥1 weekend day) of ActiGraph data were asked to re-wear the accelerometer for a required number of days (Davis & Fox, 2007). Fourteen participants were excluded from the study because they did not provide valid accelerometry data, giving a final subsample of 402 participants with objective MVPA and sedentary time data.

### 2.4. Data analyses

Descriptive statistics of all variables were computed for the total sample ($N = 909$) as well as the subsample with accelerometry data ($n = 402$). Differences between participants recruited from the Elderly Health Centres and senior community centres were examined. This study aimed to quantify the associations of perceived neighbourhood attributes with older adults' objectively-assessed and self-reported MVPA and sedentary time, mediators underlying these associations and the moderating role of sex (Fig. 1). For this purpose, we used generalised additive mixed models (GAMMs) accounting for the two-stage sampling strategy (i.e., clustering at the TPU level), possible curvilinear relationships, and with appropriate variance and link functions. Specifically, Gaussian variance and identity link functions were used to model self-reported sitting time and accelerometer-based sedentary time. Regression coefficients from such models represent the expected difference in the outcome associated with a 1 unit increase in the exposure. Gamma variance and logarithmic link functions were used to model self-reported physical activity and accelerometer-based MVPA. The exponentiated regression coefficients derived from these models represent the expected proportional difference in the outcome associated with a 1 unit increase in the exposure. Mediation models and selection of confounders for total-effect models were informed by directed acyclic graphs (Supplementary Material; Fig. S1 and Table S1). Separate sets of models were estimated for self-reported and accelerometer-based measures of MVPA and sedentary time. We assessed multicollinearity using the Variance Inflation Factor (VIF) values of all variables included in GAMMs, with a VIF > 5 considered to be problematic (Sheather, 2009). Standard diagnostics were conducted to check the validity of model assumptions.

We first estimated the total effects of perceived environmental attributes on the MVPA and sedentary time outcomes, and the moderating role of sex in these associations. Here, a 'total effect' is defined as the (confounder-adjusted) association of an environmental attribute with an outcome unadjusted for potential mediators. It represents the sum of the mediated and unmediated effects of an exposure on the outcome. Significant moderation effects of sex were probed by estimating associations for females and males.

The joint-significance test (MacKinnon & Luecken, 2008) was used to estimate the associations of perceived environmental attributes with MVPA and sedentary time mediated and unmediated by other perceived environmental attributes, and the associations of environmental

**Table 1**
Sample characteristics.

| Characteristics [theoretical range] | Whole sample (N = 909) | Subsample with accelerometer data (n = 402) |
|---|---|---|
| Socio-demographics | | |
| Age (years) | 76.5 ± 6.0 | 75.5 ± 6.2 |
| Sex (female) | 66.3 | 68.9 % |
| Educational attainment | | |
| ≤Primary schooling | 56.3 % | 53.2 % |
| ≥Secondary schooling | 43.7 % | 46.8 % |
| Marital status | | |
| Married or cohabiting | 59.5 % | 62.9 % |
| Widowed | 32.7 % | 28.4 % |
| Other | 7.8 % | 8.7 % |
| Household with car (yes) | 28.5 % | 28.9 % |
| Living alone (yes) | 23.1 % | 23.9 % |
| Health-related | | |
| Number of diagnosed medical conditions | 3.2 ± 2.0 | 3.1 ± 2.0 |
| Perceived neighbourhood environmental attributes | | |
| Residential density [0−1000] | 651.1 ± 152.8 | 652.1 ± 149.8 |
| Street connectivity [1–4] | 3.5 ± 0.6 | 3.6 ± 0.6 |
| Land use mix – diversity [1–5] | 3.4 ± 0.8 | 3.4 ± 0.8 |
| Access to services [1–4] | 3.7 ± 0.6 | 3.8 ± 0.5 |
| Pedestrian infrastructure & places for walking | | |
| Physical environmental barriers to walking [1–4] | 1.6 ± 0.6 | 1.6 ± 0.6 |
| Infrastructure for walking [1–4] | 3.6 ± 0.5 | 3.6 ± 0.5 |
| Indoor places for walking [1–4] | 2.6 ± 1.1 | 2.5 ± 1.0 |
| Benches/sitting facilities [1–4] | 2.5 ± 1.2 | 2.5 ± 1.2 |
| Aesthetics [1–4] | 2.7 ± 0.8 | 2.8 ± 0.8 |
| Crowdedness [1–4] | 1.6 ± 0.8 | 1.7 ± 0.8 |
| Social disorder [1–4] | 1.6 ± 0.5 | 1.6 ± 0.5 |
| Traffic and road hazards [1–4] | 1.9 ± 0.5 | 1.9 ± 0.5 |
| Physical activity and sedentary time (min/day) | | |
| Self-reported physical activity | 106.5 ± 81.3 | 110.6 ± 83.6 |
| Self-reported non-walking MVPA | 47.8 ± 68.1 | 51.9 ± 73.4 |
| Self-reported walking for transport | 34.5 ± 34.6 | 36.2 ± 31.8 |
| Self-reported walking for recreation | 24.3 ± 34.7 | 22.5 ± 31.7 |
| Self-reported sitting time | 280.4 ± 134.2 | 285.6 ± 142.6 |
| Accelerometer-based MVPA | NA | 69.0 ± 36.3 |
| Accelerometer-based sedentary time | NA | 404.9 ± 98.1 |
| Accelerometer wear time | NA | 810.6 ± 91.7 |

***Note.*** Values represent means ± SD or %. MVPA, moderate-to-vigorous physical activity.

attributes with sedentary time mediated and unmediated by MVPA, as depicted in Fig. 1. For a variable to be considered a mediator of an exposure-outcome association, the confounder-adjusted associations between an exposure and its mediator(s), and the confounder- and exposure-adjusted associations between the mediator(s) and the outcome need to be statistically significant. Data analyses, including mediation models, are detailed in the Supplementary Material (section S3). All analyses were conducted in R version 4.0.4.

## 3. Results

Most study participants were women, married or cohabiting, with primary schooling and from households without a private car (Table 1). High mean levels of perceived residential density, street connectivity, land use mix - diversity, access to services and infrastructure for walking, and low mean levels of physical environmental barriers to walking and social disorder were reported. The total sample and subsample of participants with accelerometer data had similar sociodemographic characteristics, average scores on the NEWS-CS subscales and average daily minutes of self-reported physical activity and sitting time (Table 1). Participants recruited from the Elderly Health Centres were more likely to be males ($p < 0.001$), less likely to live alone ($p = 0.019$), accumulate less accelerometer-based MVPA ($p = 0.024$) and report more sitting time ($p = 0.012$) than those recruited from senior community centres. No other significant differences were found between the two groups.

### 3.1. Physical activity outcomes

Four out of 12 perceived environmental attributes were significantly positively associated with self-reported physical activity in the total-effect models (unadjusted for potential environmental mediators) (Table 2). These were land use mix – diversity, access to services, availability of benches/sitting facilities and infrastructure for walking (in men only). Similar associations were observed with self-reported non-walking physical activity (Table S5). Neighbourhood aesthetics showed a U-shaped relationship with self-reported physical activity (Fig. 2) and a J-shaped relationship with walking for transport (Table S5 and Fig. S11). Access to services and infrastructure for walking were also positively related to walking for transport, while access to services and land use mix – diversity showed positive associations with walking for recreation but only in men (Table S5). Benches/sitting facilities were also predictive of more walking for recreation (Table S5) and curvilinearly related to walking for transport (Fig. S10). Street connectivity was only positively associated with walking for transport in women and traffic and road hazards were only negatively associated with the same outcome in men. Physical environmental barriers to walking and social disorder were negatively related to both walking outcomes (Table S5).

The results from the direct-effect models of self-reported physical activity were like those of the total-effect models with the exception of land use mix – diversity, which was indirectly (via access to services) rather than directly related to this outcome (Table S2 and Fig. 3). It is also noteworthy that while only access to services, benches/sitting facilities, infrastructure for walking and aesthetics were directly related to self-reported physical activity, six other attributes showed significant

**Table 2**
Associations of perceived neighbourhood environmental attributes with physical activity and sedentary time (total effect models).

| Environmental attributes [theoretical range] | Self-report measures | | | | Accelerometer-based measures | | | |
|---|---|---|---|---|---|---|---|---|
| | Physical activity | | Sitting time | | MVPA | | Sedentary time | |
| | $e^b$ (95 % CI) | *p* | *b* (95 % CI) | *p* | $e^b$ (95 % CI) | *p* | *b* (95 % CI) | *p* |
| Residential density [0–1000] | 1.0000<br>(0.9997, 1.0003) | 0.962 | **0.11**<br>**(0.05, 0.17)** | **<0.001** | **F: 0.9994**<br>**(0.9990, 0.9999)**<br>M: 1.0003<br>(0.9997, 1.0009) | **0.008**<br><br>0.251 | 0.009<br>(−0.049, 0.067) | 0.752 |
| Street connectivity [1–4] | 0.988<br>(0.911, 1.071) | 0.767 | 7.75<br>(−6.79, 22.29) | 0.296 | 0.973<br>(0.891, 1.062) | 0.543 | −1.40<br>(0.83, 6.43) | 0.064 |
| Land use mix – diversity [1–5] | **1.068**<br>**(1.002, 1.139)** | **0.045** | **−12.79**<br>**(−25.56, −0.02)** | **0.048** | **1.114**<br>**(1.033, 1.205)** | **0.005** | −9.18<br>(−22.12, 3.77) | 0.164 |
| Access to services [1–4] | **1.235**<br>**(1.083, 1.407)** | **0.002** | −2.53<br>(−24.08, 19.01) | 0.817 | F: 0.963<br>(0.833, 1.113)<br>**M: 1.350**<br>**(1.072, 1.698)** | 0.613<br><br>**0.018** | −1.54<br>(−23.88, 23.57) | 0.990 |
| Physical environmental barriers to walking [1–4] | 0.967<br>(0.888, 1.050) | 0.414 | −3.41<br>(−18.68, 11.87) | 0.662 | 0.936<br>(0.857, 1.022) | 0.137 | 5.88<br>(−8.84, 20.60) | 0.433 |
| Infrastructure for walking [1–4] | F: 1.061<br>(0.939, 1.199)<br>**M: 1.309**<br>**(1.121, 1.528)** | 0.340<br><br>**<0.001** | −2.18<br>(−20.91, 16.55) | 0.819 | F: 0.979<br>(0.861, 1.113)<br>**M: 1.269**<br>**(1.062, 1.516)** | 0.744<br><br>**0.009** | **1.90**<br>**(0.13, 38.05)** | **0.048** |
| Indoor places for walking [1–4] | 0.973<br>(0.922, 1.028) | 0.329 | −3.33<br>(13.44, 6.78) | 0.518 | 0.965<br>(0.912, 1.021) | 0.218 | 4.32<br>(−5.18, 13.81) | 0.372 |
| Benches/sitting facilities [1–4] | **1.051**<br>**(1.007, 1.096)** | **0.024** | 3.83<br>(−3.97, 11.64) | 0.335 | 1.007<br>(0.962, 1.056) | 0.735 | −1.22<br>(−9.07, 6.64) | 0.761 |
| Aesthetics [1–4] | ***F*-ratio (2.72, 892.28) = 6.19** (see Fig. 2) | **0.001** | **−15.97**<br>**(−28.61, −3.34)** | **0.013** | 1.003<br>(0.934, 1.076) | 0.938 | −3.91<br>(−15.62, 7.79) | 0.511 |
| Crowdedness [1–4] | 0.969<br>(0.906, 1.035) | 0.346 | −1.53<br>(−13.73, 10.67) | 0.805 | 1.030<br>(0.962, 1.103) | 0.387 | −7.26<br>(−18.61, 4.09) | 0.209 |
| Social disorder [1–4] | 0.961<br>(0.864, 1.070) | 0.469 | **−20.01**<br>**(−39.06, −0.96)** | **0.040** | **1.136**<br>**(1.011, 1.275)** | **0.031** | **−24.87**<br>**(−44.21, −5.53)** | **0.011** |
| Traffic and road hazards [1–4] | 1.026<br>(0.911, 1.156) | 0.670 | 0.47<br>(−20.89, 21.84) | 0.965 | **F: 0.865**<br>**(0.749, 0.999)**<br>M: 1.118<br>(0.898, 1.393) | **0.048**<br><br>0.316 | 3.98<br>(−16.77, 24.73) | 0.706 |

*Notes. F*-ratio, F-ratio for smooth term defining a curvilinear relationship; *b*, regression coefficient (from regression models with Gaussian variance and identity link functions); CI, confidence interval; $e^b$, exponentiated regression coefficient (from regression models with Gamma variance and logarithmic link function); *p*, *p*-value; MVPA, moderate-to-vigorous physical activity. For associations moderated by sex we report estimates for females (F: …) and estimates for males (M: …). Models adjusted for covariates/confounders reported in Table S1. In bold, estimates significant at a 0.05 or smaller probability level.

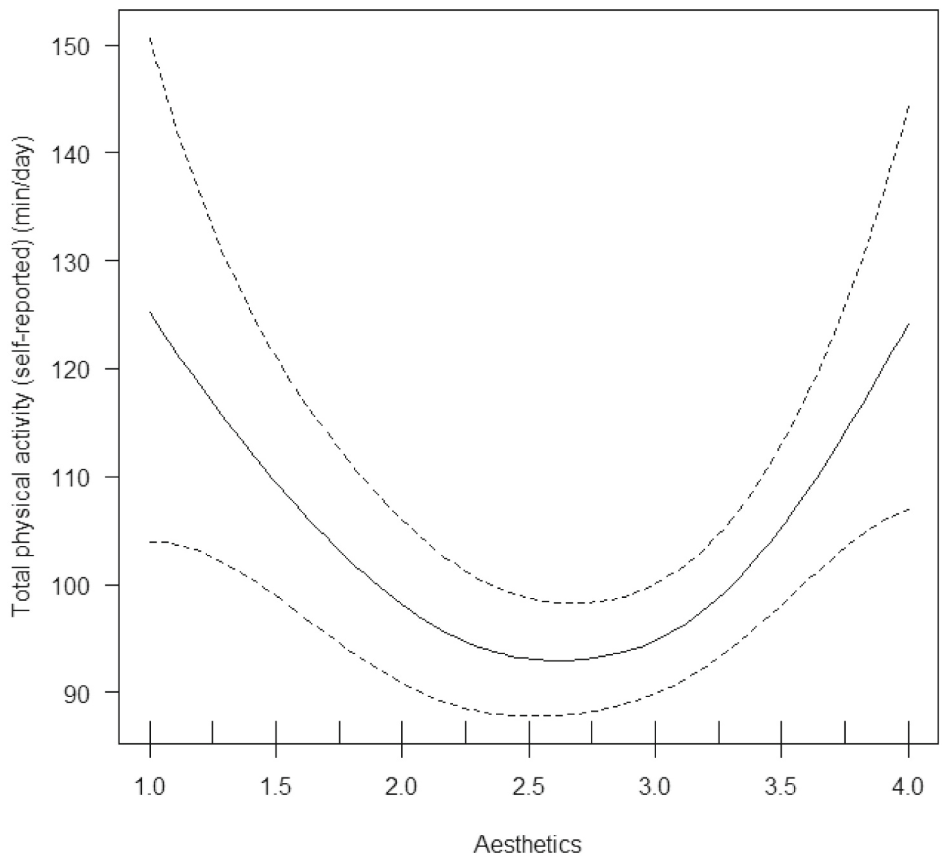


**Fig. 2.** Relationships between perceived neighbourhood aesthetics and self-reported physical activity (total-effect model; whole sample). Dashed lines represent 95 % confidence intervals.

indirect effects via these four perceived environmental attributes (Fig. S2 and 3). The indirect effects of street connectivity, land use mix – diversity and indoor places for walking were positive, those of physical environmental barriers to walking were negative and those of residential density were curvilinear (Fig. 3 and S2; Tables S2 and S3).

The perceived environmental correlates of accelerometer-based MVPA differed from those of self-reported physical activity, although a few similarities were observed, including the positive associations with land use mix – diversity and infrastructure for walking (in men only) in the total-effect models (Table 2). A positive association between access to services and MVPA was also observed but only in men. Unlike self-reported physical activity, in the total-effect models, accelerometer-based MVPA was negatively associated with residential density and with traffic and road hazards in women, and positively associated with social disorder (Table 2). Again, the direct-effect models yielded similar findings. Differences from total-effect models included residential density being negatively related to MVPA in all, traffic and roads hazards being unrelated to MVPA, and infrastructure for walking being indirectly rather than directly related to MVPA through access to services (Fig. 4). In addition, crowdedness had a positive indirect effect on MVPA through social disorder, and street connectivity had a positive effect on MVPA in men via access to services (Fig. 4).

### 3.2. Sedentary time

In the total-effect models, negative associations were observed between self-reported sitting and perceived land use mix – diversity, aesthetics and social disorder, while residential density showed a positive association (Table 2). The direct-effect models produced similar results except for land use mix – diversity which was negatively related to sitting via crowdedness and social disorder and via access to services and self-reported physical activity (Fig. 3). The fact that physical activity was significantly negatively associated with sitting time after adjusting for perceived environmental attributes means that it was also significantly indirectly related to all proximal and distal perceived environmental correlates of self-reported physical activity but in the opposite direction. For example, availability of benches/sitting facilities was directly positively associated with self-reported physical activity but indirectly negatively associated with sitting time via self-reported physical activity (Fig. 3). If we consider both direct and indirect perceived environmental correlates, self-reported sitting time was significantly related to 11 out of the 12 perceived neighbourhood attributes included in this study.

The total-effect models of accelerometer-based sedentary time revealed only three statistically significant or marginally significant perceived environmental correlates. These were infrastructure for walking, street connectivity and social disorder, with the latter two showing a negative association and the former showing a positive association (Table 2). Infrastructure for walking and street connectivity remained significant correlates in the direct-effect models, while the negative association of social disorder with sedentary time was mediated by MVPA (Fig. 4). Another perceived environmental correlate of accelerometer-based sedentary time was access to services which showed a positive association in men only (Fig. 4). Other perceived environmental attributes related of sedentary time via MVPA or other environmental attributes included: social disorder and crowdedness with negative indirect effects; land use mix – diversity with both negative and positive indirect effects; and residential density with indirect

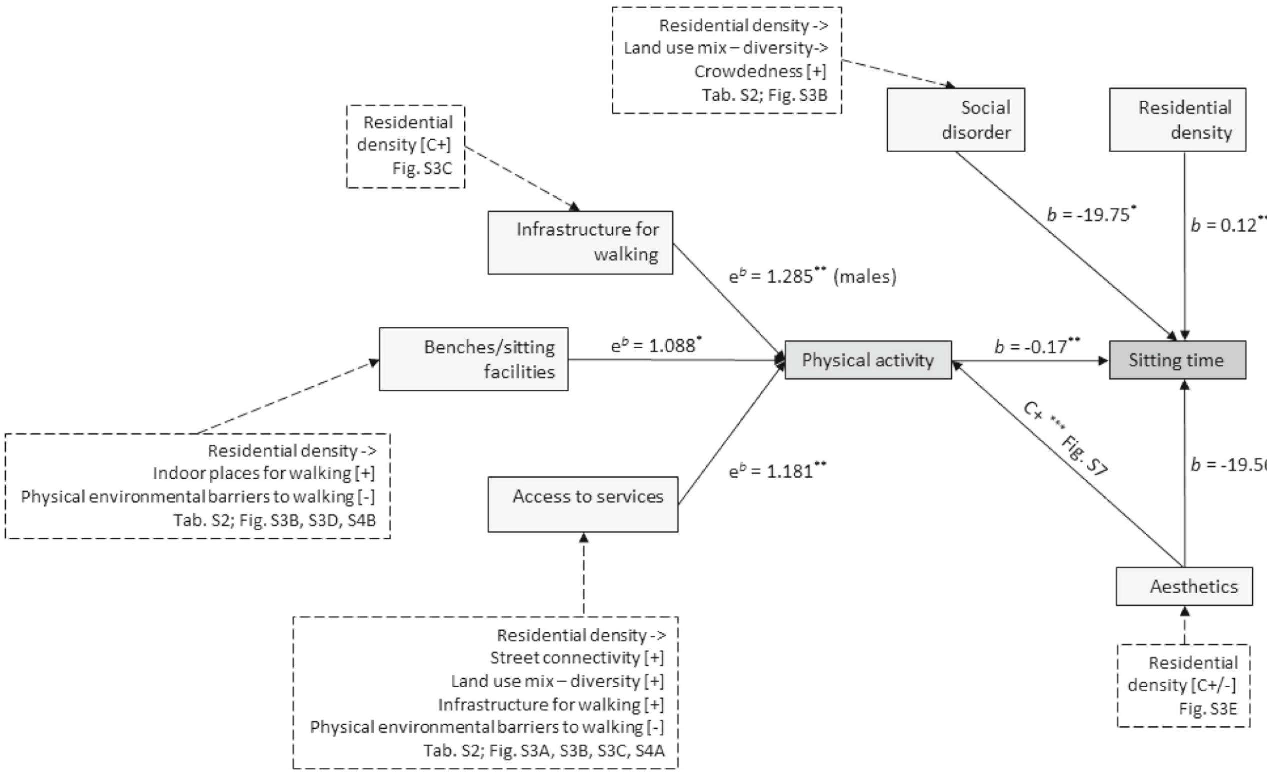


**Fig. 3.** Associations of perceived neighbourhood environment attributes with self-reported physical activity and sitting time (direct- and indirect-effect models). Only significant associations ($p < 0.05$) are reported. $e^b$ are exponentiated regression coefficients; $b$ are regression coefficients. C+ and C+/− indicate, respectively, curvilinear monotonic positive and non-monotonic relationships. Fig. #a refers to the figure depicting a curvilinear relationship (e.g., Fig. S3A is Fig. S3, panel A). Text boxes with dashed lines report perceived environmental attributes indirectly [−>] or directly positively [+], negatively [−] or curvilinearly [C] associated with other perceived neighbourhood attributes directly related to the outcomes. Point estimates and confidence intervals of all examined associations are reported in the Supplementary Material: Table S2. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

positive, negative and curvilinear effects (Fig. 4). Overall, seven out of 12 perceived environmental attributes were directly or indirectly related to accelerometer-based sedentary time.

## 4. Discussion

The main aim of this study was to examine to the strength and shape of associations of perceived neighbourhood attributes with accelerometry-assessed and self-reported physical activity and sedentary time in older adults living in an Asian ultra-dense metropolis, Hong Kong. All examined perceived neighbourhood environment attributes were directly or indirectly related to self-reported MVPA except for social disorder and traffic/road hazards, and all attributes were directly or indirectly associated with self-reported sitting time except for traffic/road hazards. Fewer perceived neighbourhood attributes showed significant associations with accelerometry-based MVPA and sedentary time. Most associations between perceived neighbourhood attributes and sedentary/sitting time were mediated by MVPA. While a substantial number of associations among environmental attributes were curvilinear, only a few environment-activity associations were sex specific.

Unlike previous research on perceived environmental correlates of older adults' physical activity and sedentary time, this study adopted a novel conceptual and analytical framework acknowledging the causal interdependence of neighbourhood environmental attributes, physical activity and sedentary time. Most of the published literature in this field reports statistical effects (associations) of perceived environmental attributes unadjusted and adjusted for other environmental attributes rather than estimating the total, direct and indirect effects of the same. This widespread analytical approach can be problematic because, as shown in Fig. 1, the unadjusted effect of an environmental attribute (e.g., street connectivity) is most likely confounded by other environmental attributes (e.g., dwelling density). Moreover, the effect of an environmental attribute (e.g., street connectivity) fully adjusted for other attributes provides information on the direct effect of the attribute but may miss important indirect effects via environmental (e.g., access to services) or behavioural (e.g., physical activity) mediators. This may lead to underestimating the importance of specific environmental features, and/or the environment in general, for the promotion of an active lifestyle. In fact, in the present study, only four out of 12 perceived environmental attributes were directly associated with each of the physical activity and sedentary time outcomes, while five to six were indirectly related to physical activity and seven to ten to sedentary time (Figs. 3 and 4). These associations would have been missed if we had solely focused on the total and (fully adjusted) direct effect, as per common practice.

### 4.1. Perceived neighbourhood attributes and physical activity

As densification influences other aspects of the neighbourhood environment (Fig. 1), we will discuss the findings of this study starting from perceived residential density as a correlate of older adults' physical activity. We hypothesised that higher residential density would be associated with environmental features that facilitate (e.g., better access to services) and others that hinder (e.g., lower levels of environmental aesthetics) participation in physical activity. This means that the total effect of perceived residential density on overall physical activity is often nil but can also be positive or negative, as evidenced by several systematic reviews (Barnett et al., 2017; Cerin et al., 2017; Van Cauwenberg et al., 2018) and this study. The negative total and direct associations observed between perceived residential density and

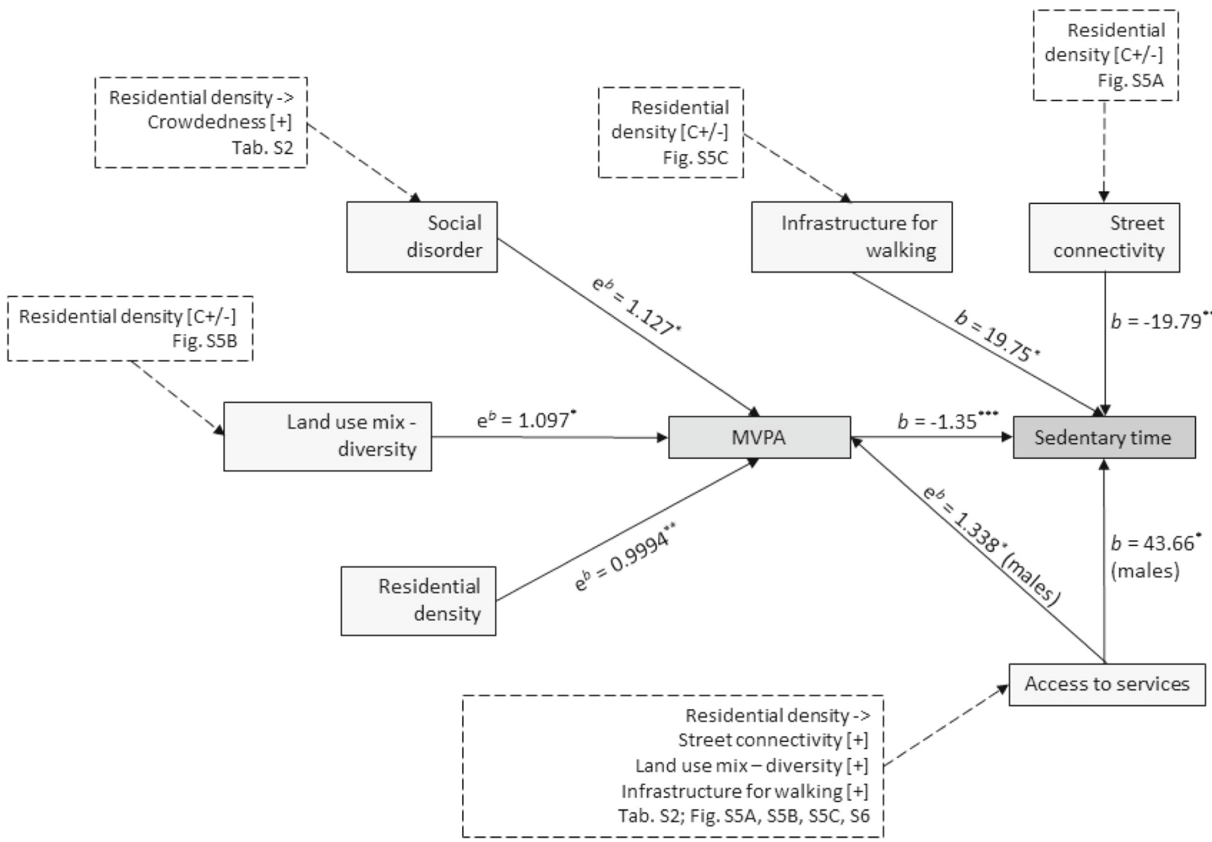


**Fig. 4.** Associations of perceived neighbourhood environment attributes with accelerometer-based moderate-to-vigorous physical activity (MVPA) and sedentary time (direct- and indirect-effect models). Only significant associations ($p < 0.05$) are reported. $e^b$ are exponentiated regression coefficients; *b* are regression coefficients. C+/− indicates curvilinear non-monotonic relationships. Fig. #a refers to the figure depicting a curvilinear relationship (e.g., Fig. S5A is Fig. S5, panel A). Text boxes with dashed lines report perceived environmental attributes indirectly [−>] or directly positively [+] or curvilinearly [C] associated with other perceived neighbourhood attributes directly related to the outcomes. Point estimates and confidence intervals of all examined associations are reported in the Supplementary Material: Table S2. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

accelerometer-based MVPA in females and the whole sample, respectively, may be due to the smaller size of dwellings and lack of private gardens found in high density neighbourhoods requiring less housework (Cerin, Van Dyck, et al., 2020). This supposition is supported by non-walking physical activity (some of which is housework) being the only self-report physical activity measure negatively associated with residential density in this study (Table S4). Because older adults are known to spend a sizeable part of their day on household physical activities (Cerin et al., 2012; Macfarlane et al., 2011; Vilhelmson et al., 2022), lower volumes of such activities can plausibly result in lower volumes of total physical activity in this demographic.

This study suggests that the negative effects of densification on older adults' physical activity accumulated through domestic work are in part offset by the provision of neighbourhoods perceived to have better pedestrian infrastructure and access to services, which support walking and leisure-time physical activity (Barnett et al., 2017; Cerin et al., 2017; Fleig et al., 2016; Van Cauwenberg et al., 2018). In fact, we found positive direct or indirect associations of physical activity with perceived infrastructure for walking, street connectivity, land use mix and access to services, all neighbourhood features positively related to residential density. We also observed indirect negative associations of physical environmental barriers to walking with physical activity. Here, it is important to note that, while the associations between physical activity and these environmental mediators of residential density were linear, those between residential density and the mediators were curvilinear, suggesting threshold values at the high end of residential density beyond which no further improvements, or even reductions, in perceived walkability occur. In this regard, a recent multi-country study on thresholds of urban design features associated with walking estimated that neighbourhoods should have density levels between 5700 and ~18,000 people/km$^2$ to promote active living (Cerin, Sallis, et al., 2022). In Hong Kong, the density of neighbourhoods across the walkability spectrum ranges from 37 to ~39,000 dwellings/km$^2$ (equivalent to 100 to ~105,000 people/km$^2$) (Cerin, Van Dyck, et al., 2020). It appears that while higher density may help accrue more physical activity by providing the infrastructure and motivation for walking, extreme levels of density may not be optimal for physical activity.

Another neighbourhood feature influenced by residential density that emerged as an important correlate of older adults' physical activity, especially walking for recreation and other non-walking physical activities, is the availability of benches and other sitting facilities. Sitting facilities make it possible for older people with reduced physical capacity to rest during their walks and other leisure-time physical activities (e.g., tai chi). Both qualitative (Gallagher et al., 2010; Van Cauwenberg et al., 2012) and quantitative studies (Cerin et al., 2017) have identified the lack of sitting facilities as a major barrier to older adults' walking. Our study suggests that, in Hong Kong, neighbourhoods with moderate levels of residential density may be more activity-friendly than lower density neighbourhoods because they provide more indoor places for walking where sitting facilities are available, and more activity-friendly than higher density neighbourhoods because they have more outdoor space for benches.

Perceived aesthetics, another environmental mediator of residential density, showed complex, curvilinear relationships with residential density as well as physical activity. As expected, perceived residential density was generally negatively associated with aesthetics. Contrary to expectations, older adults living in neighbourhoods perceived to have low or high levels of aesthetics reported more physical activity than those living in neighbourhoods with moderate levels of aesthetics. Supplementary analyses indicated that this effect was attributable to the association between aesthetics and walking for transport. Neighbourhoods rich in commercial outlets, but typically lacking greenery and attractive architectural features, are places where most residents would engage in walking for transport for their daily needs. Green, interesting and attractive neighbourhoods may motivate walking to/from local interesting places despite them not offering a wide range of commercial services. Our findings contrast with the published literature reporting positive effects of aesthetics on physical activity (Cerin et al., 2019) possibly partly due to differences in the urban form of the study locations, and previous studies not adjusting for potential environmental confounders or examining the curvilinearity of the associations.

As for perceived aesthetics, the relationship between perceived residential density and social disorder were in the expected direction (i.e., positive and mediated by crowdedness) but those of social disorder with physical activity were not. Older adults reporting higher levels of social disorder in the neighbourhood engaged in more accelerometer-assessed MVPA. Given that perceived social disorder was, as anticipated, negatively associated with both walking for transport and walking for recreation (Tables S4 and S5), it is plausible to assume that neighbourhood social disorder may be an indicator of area-level disadvantage and Hong Kong older adults living in such neighbourhoods accrued MVPA through occupational physical activity. In fact, Hong Kong older adults in the labour force typically have a lower educational attainment and engage in lower-skill, low-paid occupations often involving MVPA (e.g., construction, machine operators and elementary manual labour) (Legislative Council Secretariat, 2018).

We observed sex-specific associations between two indicators of perceived neighbourhood walkability, perceived traffic and physical activity. Infrastructure for walking and access to services showed positive total and direct effects on physical activity in males only, while a total negative effect of traffic and road hazards on physical activity was found in females. Supplementary analyses indicated that male-specific associations may be attributable to older Hong Kong men from neighbourhoods with better access to services walking for recreation more than their counterparts. In the context of Hong Kong culture, men may engage in more walking in the neighbourhood for leisure if they have access to a variety of destinations of interest. In contrast, older women are likely to follow traditional gender roles including taking control of daily household-related duties such as grocery shopping (Inoue et al., 2011; Sin et al., 2001) and, thus, may accumulate a substantial amount of physical activity via utilitarian walking within and outside their neighbourhood independently of their perceived level of access to services in their local area. That utilitarian rather than recreation walking may be more relevant to older Hong Kong women is also consistent with the positive association observed between perceived street connectivity and walking for transport in this demographic. The fact that older women who perceive more traffic hazards accumulate less MVPA may be attributable to them being more cautious than men when walking in trafficked areas (Foster et al., 2004).

### 4.2. Perceived neighbourhood attributes and sedentary time

Because, as anticipated, physical activity was negatively related to sedentary time, all perceived environmental attributes showing a direct or indirect association with physical activity were also indirectly (via physical activity) associated with sedentary time but in the opposite direction. Therefore, we can conclude that older residents living in neighbourhoods perceived to have better pedestrian infrastructure and a wide range of destinations might spend less time on sedentary activities because they allocate more time to physically active pursuits, which is consistent with findings from other populations of older adults (Cerin et al., 2021; Cerin, Van Dyck, et al., 2020; Fleig et al., 2016; Greenwood-Hickman et al., 2022; Oyeyemi et al., 2019). It is interesting that, while residential density and social disorder showed direct positive and negative associations with self-reported sitting time, respectively, these associations with accelerometer-based sedentary time were channelled via physical activity (MVPA). These (and other) discrepant results between self-report and accelerometer-based measures of activity may be due to measurement error as well as substantive differences between the outcome measures. Indeed, sitting time and sedentary time are different, albeit related, constructs (Tremblay et al., 2017). Occupational and household physical activities may not be as accurately reflected in the self-reported estimates of total physical activity as in the accelerometry-based MVPA because it is challenging to accurately recall the amount of time and intensity spent in such unstructured activities (Chasan-Taber et al., 2002; Collins et al., 2007; Kwak et al., 2011).

Several perceived environmental attributes showed distinctive associations with sedentary time. As hypothesised based on earlier studies (Cerin et al., 2021; Fleig et al., 2016), perceived aesthetics and street connectivity were negatively associated with measures of sedentary time. However, these associations were not mediated by physical activity. In the context of Hong Kong, neighbourhood aesthetics and connectivity may help older adults replace sedentary time with some light intensity activities (e.g., strolling and socialising in the neighbourhood) that were not captured by our physical activity measures. High levels of street connectivity may also result in pedestrians walking at a slower pace due to having to cross roads more frequently. We also found unexpected positive direct associations of infrastructure for walking and access to services (in males only) with accelerometer-based sedentary time but not self-reported sitting time. While walkable neighbourhoods provide opportunities for walking and engagement in active leisure-time pursuits, they also provide opportunities for sedentary leisure-time activities. This may explain why these two environmental features showed positive associations with physical activity as well as sedentary time. In a similar fashion, an earlier study of Hong Kong older adults found places of worship in the neighbourhood to be positively associated with self-reported sitting time (Barnett et al., 2015) and walking for transport (Cerin et al., 2013).

### 4.3. Study strengths and limitations

Study strengths include: the high response rate (71 %); the stratified sampling strategy chosen to maximise the variability in environmental exposures and outcomes; using exposure and outcome measures specifically developed for, and validated in, the target population (Barnett et al., 2016; Cerin et al., 2010; Cerin et al., 2011); the assessment of self-report as well as device-based measures of physical activity and sedentary time; interviewer-administered surveys conducted by trained interviewers enabling clarity (van Uffelen et al., 2011) and, consequently, more accurate data; and the novel analytical approach acknowledging the interdependence between the various exposures and outcomes, and the presence of curvilinear effects.

There were also several limitations. The cross-sectional nature of the study limits the evidence of causality needed to make unequivocable recommendations for policy changes and interventions. Future longitudinal and quasi-experimental research (e.g., natural experiments) may allow for firmer conclusions to be drawn. As it was not possible to obtain a comprehensive sampling frame for participant recruitment across Hong Kong neighbourhoods due to privacy ordinance restrictions (Cerin et al., 2016), participants were recruited in person from elderly health centres and community centres. This may have resulted in a certain level of sampling bias and an underestimation of environment-physical activity associations given that members of elderly health centres tend to be more physically active than their counterparts (Sun et al., 2012). However, the purposeful recruitment of participants from different socio-economic and environmental strata (Cerin et al., 2016) may have helped mitigate this issue. Eligibility criteria excluded participants unable to walk for a short distance without major difficulties. Waist-worn accelerometers do not distinguish sitting from other sedentary types of sedentary behaviours (Berendsen et al., 2014). The use of inclinometers (Berendsen et al., 2014) would have provided a measure comparable to that of self-reported sitting time. This study focused on perceived neighbourhood environment attributes that, by their nature, may not accurately reflect the objective environment and, hence, may not provide solid evidence-based information to guide urban planning policy and practice. Future studies need to examine how objectively assessed and perceived neighbourhood attributes relate to one another and how they jointly affect older adults' physical activity and sedentary behaviours.

### *4.4. Conclusions and practical implications*

Our study suggests that older adults who perceive their neighbourhood to be walkable (i.e., with good pedestrian infrastructure and a well-connected network providing easy access to a wide range of amenities), safe, aesthetically pleasing and equipped with public sitting facilities are, in general, more likely to lead an active lifestyle, i.e., engage in more physical activity and accumulate less sedentary time. Hence, urban planners should aim to provide these activity-friendly urban design features in residential areas. The presence of many such features, including access to services and street connectivity, relies on sufficient levels of residential density. However, aiming for extreme levels of density in ultra-dense cities may not be optimal for leading an active lifestyle because they may not provide sufficient space for sitting facilities and greenery and, at the same time, may not result in better perceptions of neighbourhood walkability when compared to areas with moderate-to-high levels of density. Also, living in ultra-dense neighbourhoods may reduce the opportunities for housework and gardening, which can significantly contribute to the overall accumulation of health-enhancing levels of physical activity in older adults. All these findings point at the need to operationalise optimal levels of residential density for health that can serve as measurable policy targets to urban planners. Future studies should establish robust threshold values of objective residential density optimal for the promotion of an active lifestyle in ageing populations in megacities. Furthermore, residents of dense neighbourhoods may benefit from creative solutions aiming to incorporate greenery, community gardens and public places for sitting, the utility of which needs to be corroborated with objective environmental data.

## CRediT authorship contribution statement

**Ester Cerin:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Funding acquisition. **Casper J.P. Zhang:** Investigation, Project administration, Writing – review & editing. **David W. Barnett:** Writing – original draft, Writing – review & editing. **Ruby S.Y. Lee:** Writing – review & editing, Funding acquisition. **Cindy H.P. Sit:** Writing – review & editing, Funding acquisition. **Anthony Barnett:** Writing – review & editing, Funding acquisition.

## Declaration of competing interest

None.

## Data availability

The data used in this paper include personal residential information as well as health-related information. Therefore, the data are not publicly available due to privacy concerns. Data are, however, available from the corresponding author upon reasonable request after obtaining permission from the Department of Health, Hong Kong SAR in accordance with the ethics policy statements related to the study protocol.


### *Acknowledgement*

Not applicable.

### *Funding source declaration*

This work was supported by a General Research Fund grant from the University Grant Committee (Hong Kong) [HKU741511H]. The funding body had no role in study design, data collection and analysis, interpretation of data, decision to publish, or writing of the manuscript.


## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cities.2023.104518.

## References


Adams, M. A., Frank, L. D., Schipperijn, J., Smith, G., Chapman, J., Christiansen, L. B., … Sallis, J. F. (2014). International variation in neighborhood walkability, transit, and recreation environments using geographic information systems: The IPEN adult study. *International Journal of Health Geographics, 13*(1), 43. https://doi.org/10.1186/1476-072X-13-43

Aguilar-Farías, N., Brown, W. J., & Peeters, G. M. (2014). ActiGraph GT3X+ cut-points for identifying sedentary behaviour in older adults in free-living environments. *Journal of Science and Medicine in Sport, 17*(3), 293–299. https://doi.org/10.1016/j.jsams.2013.07.002

Amagasa, S., Inoue, S., Fukushima, N., Kikuchi, H., Nakaya, T., Hanibuchi, T., … Owen, N. (2019). Associations of neighborhood walkability with intensity- and bout-specific physical activity and sedentary behavior of older adults in Japan. *Geriatrics & Gerontology International, 19*(9), 861–867. https://doi.org/10.1111/ggi.13730

Arnardottir, N. Y., Koster, A., Van Domelen, D. R., Brychta, R. J., Caserotti, P., Eiriksdottir, G., … Sveinsson, T. (2013). Objective measurements of daily physical activity patterns and sedentary behaviour in older adults: Age, gene/environment susceptibility-Reykjavik Study. *Age and Ageing, 42*(2), 222–229. https://doi.org/10.1093/ageing/afs160

Barnett, A., Cerin, E., Ching, C. S. K., Johnston, J. M., & Lee, R. S. Y. (2015). Neighbourhood environment, sitting time and motorised transport in older adults: A cross-sectional study in Hong Kong. *BMJ Open, 5*(4), Article e007557. https://doi.org/10.1136/bmjopen-2014-007557

Barnett, A., van den Hoek, D., Barnett, D., & Cerin, E. (2016). Measuring moderate-intensity walking in older adults using the ActiGraph accelerometer. *BMC Geriatrics, 16*(1), 211. https://doi.org/10.1186/s12877-016-0380-5

Barnett, D. W., Barnett, A., Nathan, A., Van Cauwenberg, J., Cerin, E., & on behalf of the Council on, E., & Physical Activity – Older Adults working, g. (2017). Built environmental correlates of older adults' total physical activity and walking: A systematic review and meta-analysis. *International Journal of Behavioral Nutrition and Physical Activity, 14*(1), 103. https://doi.org/10.1186/s12966-017-0558-z

Berendsen, B. A. J., Hendriks, M. R. C., Meijer, K., Plasqui, G., Schaper, N. C., & Savelberg, H. H. C. M. (2014). Which activity monitor to use? Validity, reproducibility and user friendliness of three activity monitors. *BMC Public Health, 14*(1), 749. https://doi.org/10.1186/1471-2458-14-749

Boakye-Dankwa, E., Nathan, A., Barnett, A., Busija, L., Lee, R. S. Y., Pachana, N., … Cerin, E. (2019). Walking behaviour and patterns of perceived access to neighbourhood destinations in older adults from a low-density (Brisbane, Australia) and an ultra-dense city (Hong Kong, China). *Cities, 84*, 23–33. https://doi.org/10.1016/j.cities.2018.07.002

Brownson, R. C., Hoehner, C. M., Day, K., Forsyth, A., & Sallis, J. F. (2009). Measuring the built environment for physical activity: State of the science. *American Journal of Preventive Medicine, 36*(4 Suppl), S99–123.e112. https://doi.org/10.1016/j.amepre.2009.01.005

Buman, M. P., Hekler, E. B., Haskell, W. L., Pruitt, L., Conway, T. L., Cain, K. L., … King, A. C. (2010). Objective light-intensity physical activity associations with rated health in older adults. *American Journal of Epidemiology, 172*(10), 1155–1165. https://doi.org/10.1093/aje/kwq249

Cerin, E., Barnett, A., Cheung, M. C., Sit, C. H., Macfarlane, D. J., & Chan, W. M. (2012). Reliability and validity of the IPAQ-L in a sample of Hong Kong urban older adults: Does neighborhood of residence matter? *Journal of Aging and Physical Activity, 20*(4), 402–420. https://doi.org/10.1123/japa.20.4.402

Cerin, E., Barnett, A., Shaw, J. E., Martino, E., Knibbs, L. D., Tham, R., … Anstey, K. J. (2021). From urban neighbourhood environments to cognitive health: A cross-sectional analysis of the role of physical activity and sedentary behaviours. *BMC Public Health, 21*(1), 2320. https://doi.org/10.1186/s12889-021-12375-3

Cerin, E., Barnett, A., Shaw, J. E., Martino, E., Knibbs, L. D., Tham, R., … Anstey, K. J. (2022). Urban neighbourhood environments, cardiometabolic health and cognitive function: A national cross-sectional study of middle-aged and older adults in Australia. *Toxics, 10*(1). https://doi.org/10.3390/toxics10010023

Cerin, E., Barnett, A., Sit, C. H. P., Cheung, M. C., Lee, L. C. J., Ho, S. Y., & Chan, W. M. (2011). Measuring walking within and outside the neighborhood in Chinese elders: Reliability and validity. *BMC Public Health, 11*(1), 851. https://doi.org/10.1186/1471-2458-11-851

Cerin, E., Barnett, A., Zhang, C. J. P., Lai, P. C., Sit, C. H. P., & Lee, R. S. Y. (2020). How urban densification shapes walking behaviours in older community dwellers: A cross-sectional analysis of potential pathways of influence. *International Journal of Health Geographics, 19*(1), 14. https://doi.org/10.1186/s12942-020-00210-8

Cerin, E., Lee, K.-y., Barnett, A., Sit, C. H. P., Cheung, M.-c., Chan, W.-m., & Johnston, J. M. (2013). Walking for transportation in Hong Kong Chinese urban elders: A cross-sectional study on what destinations matter and when. *International Journal of Behavioral Nutrition and Physical Activity, 10*(1), 78. https://doi.org/10.1186/1479-5868-10-78

Cerin, E., Nathan, A., Van Cauwenberg, J., & A., B. (2019). Neighbourhood built environment and older adults' physical activity. In A. Lane (Ed.), *Urban environments for healthy ageing: A global perspective* (pp. 69–88). Routledge.

Cerin, E., Nathan, A., van Cauwenberg, J., Barnett, D. W., Barnett, A., & on behalf of the Council on, E., & Physical Activity – Older Adults working, g. (2017). The neighbourhood physical environment and active travel in older adults: A systematic review and meta-analysis. *International Journal of Behavioral Nutrition and Physical Activity, 14*(1), 15. https://doi.org/10.1186/s12966-017-0471-5

Cerin, E., Sallis, J. F., Salvo, D., Hinckson, E., Conway, T. L., Owen, N., … Giles-Corti, B. (2022). Determining thresholds for spatial urban design and transport features that support walking to create healthy and sustainable cities: Findings from the IPEN Adult study. *Lancet Global Health, 10*(6), e895–e906. https://doi.org/10.1016/s2214-109x(22)00068-7

Cerin, E., Sit, C. H., Cheung, M. C., Ho, S. Y., Lee, L. C., & Chan, W. M. (2010). Reliable and valid NEWS for Chinese seniors: Measuring perceived neighborhood attributes related to walking. *International Journal of Behavioral Nutrition and Physical Activity, 7*, 84. https://doi.org/10.1186/1479-5868-7-84

Cerin, E., Sit, C. H., Zhang, C. J., Barnett, A., Cheung, M. M., Lai, P. C., … Lee, R. S. (2016). Neighbourhood environment, physical activity, quality of life and depressive symptoms in Hong Kong older adults: a protocol for an observational study. *BMJ Open, 6*(1), e010384. https://doi.org/10.1136/bmjopen-2015-010384

Cerin, E., Van Dyck, D., Zhang, C. J. P., Van Cauwenberg, J., Lai, P.-c., & Barnett, A. (2020). Urban environments and objectively-assessed physical activity and sedentary time in older Belgian and Chinese community dwellers: Potential pathways of influence and the moderating role of physical function. *International Journal of Behavioral Nutrition and Physical Activity, 17*(1), 73. https://doi.org/10.1186/s12966-020-00979-8

Cerin, E., Zhang, C. J. P., Barnett, A., Sit, C. H. P., Cheung, M. M. C., Johnston, J. M., … Lee, R. S. Y. (2016). Associations of objectively-assessed neighborhood characteristics with older adults' total physical activity and sedentary time in an ultra-dense urban environment: Findings from the ALECS study. *Health & Place, 42*, 1–10. https://doi.org/10.1016/j.healthplace.2016.08.009

Chasan-Taber, L., Erickson, J. B., Nasca, P. C., Chasan-Taber, S., & Freedson, P. S. (2002). Validity and reproducibility of a physical activity questionnaire in women. *Medicine & Science in Sports & Exercise, 34*(6), 987–992. https://doi.org/10.1097/00005768-200206000-00013

Choi, L., Ward, S. C., Schnelle, J. F., & Buchowski, M. S. (2012). Assessment of wear/nonwear time classification algorithms for triaxial accelerometer. *Medicine & Science in Sports & Exercise, 44*(10), 2009–2016. https://doi.org/10.1249/MSS.0b013e318258cb36

Colbert, L. H., Matthews, C. E., Havighurst, T. C., Kim, K., & Schoeller, D. A. (2011). Comparative validity of physical activity measures in older adults. *Medicine & Science in Sports & Exercise, 43*(5), 867–876. https://doi.org/10.1249/MSS.0b013e3181fc7162

Collins, B. S., Miller, Y. D., & Marshall, A. L. (2007). Physical activity in women with young children: How can we assess "anything that's not sitting"? *Women & Health, 45*(2), 95–116. https://doi.org/10.1300/J013v45n02_06

Cunningham, C., O' Sullivan, R., Caserotti, P., & Tully, M. A. (2020). Consequences of physical inactivity in older adults: A systematic review of reviews and meta-analyses [doi:10.1111/sms.13616]. *Scandinavian Journal of Medicine & Science in Sports, 30*(5), 816–827. https://doi.org/10.1111/sms.13616

Davis, M. G., & Fox, K. R. (2007). Physical activity patterns assessed by accelerometry in older people. *European Journal of Applied Physiology, 100*(5), 581–589. https://doi.org/10.1007/s00421-006-0320-8

Davis, M. G., Fox, K. R., Hillsdon, M., Sharp, D. J., Coulson, J. C., & Thompson, J. L. (2011). Objectively measured physical activity in a diverse sample of older urban UK adults. *Medicine & Science in Sports & Exercise, 43*(4), 647–654. https://doi.org/10.1249/MSS.0b013e3181f36196

de Rezende, L. F., Rey-López, J. P., Matsudo, V. K., & do Carmo Luiz, O.. (2014). Sedentary behavior and health outcomes among older adults: A systematic review. *BMC Public Health, 14*, 333. https://doi.org/10.1186/1471-2458-14-333

Deng, H. B., Macfarlane, D. J., Thomas, G. N., Lao, X. Q., Jiang, C. Q., Cheng, K. K., & Lam, T. H. (2008). Reliability and validity of the IPAQ-Chinese: The Guangzhou Biobank Cohort study. *Medicine & Science in Sports & Exercise, 40*(2), 303–307. https://doi.org/10.1249/mss.0b013e31815b0db5

Evenson, K. R., Buchner, D. M., & Morland, K. B. (2012). Objective measurement of physical activity and sedentary behavior among US adults aged 60 years or older. *Preventing Chronic Disease, 9*, E26.

Fleig, L., Ashe, M. C., Voss, C., Therrien, S., Sims-Gould, J., McKay, H. A., & Winters, M. (2016). Environmental and psychosocial correlates of objectively measured physical activity among older adults. *Health Psychology, 35*(12), 1364–1372. https://doi.org/10.1037/hea0000403

Foster, C., Hillsdon, M., & Thorogood, M. (2004). Environmental perceptions and walking in English adults. *Journal of Epidemiology and Community Health, 58*(11), 924–928. https://doi.org/10.1136/jech.2003.014068

Frank, L. D., Engelke, P. O., & Schmidt, T. L. (2003). *Health and community design: The impact of the built environment on physical activity*. Island Press.

Gallagher, N. A., Gretebeck, K. A., Robinson, J. C., Torres, E. R., Murphy, S. L., & Martyn, K. K. (2010). Neighborhood factors relevant for walking in older, urban, African American adults. *Journal of Aging and Physical Activity, 18*(1), 99–115. https://doi.org/10.1123/japa.18.1.99

Giles-Corti, B., Moudon, A. V., Lowe, M., Adlakha, D., Cerin, E., Boeing, G., … Sallis, J. F. (2022). Creating healthy and sustainable cities: What gets measured, gets done. *Lancet Global Health, 10*(6), e782–e785. https://doi.org/10.1016/s2214-109x(22)00070-5

Glass, T. A., & Balfour, J. L. (2003). Neighborhoods, aging, and functional limitations. In I. Kawachi, & L. F. Berkman (Eds.), *Neihborhoods and health* (pp. 303–334). New York: Oxford University Press.

Greenwood-Hickman, M. A., Walker, R., Bellettiere, J., LaCroix, A. Z., Kim, B., Wing, D., … Rosenberg, D. E. (2022). Associations between perceived neighborhood walkability and device-based physical activity and sedentary behavior patterns in older adults. *Journal of Aging and Physical Activity, 30*(1), 98–106. https://doi.org/10.1123/japa.2020-0387

Inoue, S., Ohya, Y., Odagiri, Y., Takamiya, T., Kamada, M., Okada, S., … Shimomitsu, T. (2011). Perceived neighborhood environment and walking for specific purposes among elderly Japanese. *Journal of Epidemiology, 21*(6), 481–490. https://doi.org/10.2188/jea.je20110044

Kwak, L., Proper, K. I., Hagströmer, M., & Sjöström, M. (2011). The repeatability and validity of questionnaires assessing occupational physical activity–a systematic review. *Scandinavian Journal of Work, Environment & Health, 37*(1), 6–29. https://doi.org/10.5271/sjweh.3085

Lee, I. M., Shiroma, E. J., Lobelo, F., Puska, P., Blair, S. N., & Katzmarzyk, P. T. (2012). Effect of physical inactivity on major non-communicable diseases worldwide: An analysis of burden of disease and life expectancy. *Lancet, 380*(9838), 219–229. https://doi.org/10.1016/s0140-6736(12)61031-9

Legislative Council Secretariat. (2018). Measures to promote employment of mature persons in selected places. https://www.legco.gov.hk/research-publications/english/1718in13-measures-to-promote-employment-of-mature-persons-in-selected-places-20180713-e.pdf.

Macfarlane, D., Chan, A., & Cerin, E. (2011). Examining the validity and reliability of the Chinese version of the International Physical Activity Questionnaire, long form (IPAQ-LC). *Public Health Nutrition, 14*(3), 443–450. https://doi.org/10.1017/s1368980010002806

MacKinnon, D. P., & Luecken, L. J. (2008). How and for whom? Mediation and moderation in health psychology. *Health Psychology, 27*(2s), S99–s100. https://doi.org/10.1037/0278-6133.27.2(Suppl.).S99

Matthews, C. E., Chen, K. Y., Freedson, P. S., Buchowski, M. S., Beech, B. M., Pate, R. R., & Troiano, R. P. (2008). Amount of time spent in sedentary behaviors in the United States, 2003-2004. *American Journal of Epidemiology, 167*(7), 875–881. https://doi.org/10.1093/aje/kwm390

O'Rourke, H. P., & MacKinnon, D. P. (2015). When the test of mediation is more powerful than the test of the total effect. *Behavior Research Methods, 47*(2), 424–442. https://doi.org/10.3758/s13428-014-0481-z

Oyeyemi, A. L., Kolo, S. M., Rufai, A. A., Oyeyemi, A. Y., Omotara, B. A., & Sallis, J. F. (2019). Associations of neighborhood walkability with sedentary time in Nigerian older adults. *International Journal of Environmental Research and Public Health, 16*(11). https://doi.org/10.3390/ijerph16111879

Sallis, J. F., Cervero, R. B., Ascher, W., Henderson, K. A., Kraft, M. K., & Kerr, J. (2006). An ecological approach to creating active living communities. *Annual Review of Public Health, 27*, 297–322. https://doi.org/10.1146/annurev.publhealth.27.021405.102100

Satariano, W. A., Guralnik, J. M., Jackson, R. J., Marottoli, R. A., Phelan, E. A., & Prohaska, T. R. (2012). Mobility and aging: New directions for public health action. *American Journal of Public Health, 102*(8), 1508–1515. https://doi.org/10.2105/ajph.2011.300631

Schooling, C. M., Lam, T. H., Li, Z. B., Ho, S. Y., Chan, W. M., Ho, K. S., … Leung, G. M. (2006). Obesity, physical activity, and mortality in a prospective Chinese elderly cohort. *Archives of Internal Medicine, 166*(14), 1498–1504. https://doi.org/10.1001/archinte.166.14.1498

Sheather, S. (2009). *A nodern approach to regression with R* (1 ed.). Springer. https://doi.org/10.1007/978-0-387-09608-7

Sin, L. Y. M., So, S. L. M., Yau, O. H. M., & Kwong, K. (2001). Chinese women at the crossroads: An empirical study on their role orientations and consumption values in Chinese society. *Journal of Consumer Marketing, 18*(4), 348–367. https://doi.org/10.1108/07363760110393010

Steinberg, S. I., Sammel, M. D., Harel, B. T., Schembri, A., Policastro, C., Bogner, H. R., … Arnold, S. E. (2015). Exercise, sedentary pastimes, and cognitive performance in healthy older adults. *American Journal of Alzheimer's Disease & Other Dementias, 30*(3), 290–298. https://doi.org/10.1177/1533317514545615

Sun, F., Norman, I. J., & While, A. E. (2013). Physical activity in older people: A systematic review. *BMC Public Health, 13*, 449. https://doi.org/10.1186/1471-2458-13-449

Sun, W. J., Xu, L., Chan, W. M., Lam, T. H., & Schooling, M. (2012). Depressive symptoms and suicide in 56,000 older Chinese: A Hong Kong cohort study. *Social Psychiatry and Psychiatric Epidemiology, 47*, 505–514. https://doi.org/10.1007/s00127-011-0362-z

Tremblay, M. S., Aubert, S., Barnes, J. D., Saunders, T. J., Carson, V., Latimer-Cheung, A. E., … on behalf of, S. T. C. P. P. (2017). Sedentary Behavior Research Network (SBRN) – Terminology consensus project process and outcome. *International Journal of Behavioral Nutrition and Physical Activity, 14*(1), 75. https://doi.org/10.1186/s12966-017-0525-8

United Nations, Department of Economic and Social Affairs, Population Division. (2013). *World Population Ageing 2013* (ST/ESA/SER.A/348). https://www.un.org/en/devel opment/desa/population/publications/pdf/ageing/WorldPopulationAgeing2013.pdf.

United Nations, Department of Economic and Social Affairs, Population Division. (2019). *World Urbanization Prospects: The 2018 Revision* (ST/ESA/SER.A/420). https://population.un.org/wup/Publications/Files/WUP2018-Report.

Van Cauwenberg, J., Nathan, A., Barnett, A., Barnett, D. W., & Cerin, E. (2018). Relationships between neighbourhood physical environmental attributes and older adults' leisure-time physical activity: A systematic review and meta-analysis. *Sports Medicine, 48*(7), 1635–1660. https://doi.org/10.1007/s40279-018-0917-1

Van Cauwenberg, J., Van Holle, V., Simons, D., Deridder, R., Clarys, P., Goubert, L., … Deforche, B. (2012). Environmental factors influencing older adults' walking for transportation: A study using walk-along interviews. *International Journal of Behavioral Nutrition and Physical Activity, 9*, 85. https://doi.org/10.1186/1479-5868-9-85

van Uffelen, J. G., Heesch, K. C., Hill, R. L., & Brown, W. J. (2011). A qualitative study of older adults' responses to sitting-time questions: Do we get the information we want? *BMC Public Health, 11*, 458. https://doi.org/10.1186/1471-2458-11-458

Vilhelmson, B., Thulin, E., & Elldér, E. (2022). Time change in the distribution of physical activity and its correlates among retired older Swedish adults: A repeated cross-sectional study from a national survey. *BMC Public Health, 22*(1), 2055. https://doi.org/10.1186/s12889-022-14554-2

World Bank Group. (2021). Population in urban agglomerations of more than 1 million (% of total population). https://data.worldbank.org/indicator/EN.URB.MCTY.TL.ZS.