Associations of neighbourhood environmental attributes and socio-economic status with health-related quality of life in urban mid-aged and older adults: Mediation by physical activity and sedentary behaviour


1. Introduction

The current trend of population ageing predicts a 34% increase in ≥60 year-olds globally from 2020 to the end of the decade (Scott, 2021). Also, the percentage of older adults (≥65 years old) in the global population is expected to increase from 9.3% in 2020 to 16% in 2050 (Population Division of the United Nations, Department of Economic and Social Affairs, 2020). Hence, it is important to identify modifiable factors that can preserve mid-aged and older adults’ health and HRQoL at a population level. As a high proportion of the world’s population now lives in cities (Population Division of the United Nations, Department of Economic and Social Affairs, 2014), the urban neighbourhood environment is a potential source of such factors.

Several studies have investigated neighbourhood environmental correlates of mid-aged and older adults’ HRQoL as assessed by versions of the Short Form Health Survey (SF), a well-validated, popular measure of HRQoL commonly used in health economics (Mortimer & Segal, 2008). Most of these have examined urban/rural environment differences (e.g., Borders et al., 2004; Byles et al., 2006; Valdivieso-Mora et al., 2018; Zhou et al., 2011), neighbourhood social capital (e.g., Apostolaki et al., 2021; Bowling et al., 2006; Luo & Menec, 2018) and/or perceived physical environment attributes (Byles et al., 2014; Chatti et al., 2017; Stephens et al., 2020; Tomney et al., 2013; Van Dyck et al., 2015; Zhao & Chung, 2017). In contrast, few studies have examined associations of objectively assessed neighbourhood physical environment attributes (Loo et al., 2017; Parra et al., 2010) or socio-economic...
status (SES) (Lucumí et al., 2015; Parra et al., 2010; Tomey et al., 2013) with HRQoL.

In an Asian urban context, Loo et al. (2017) found that neighbour-
hood population density, access to supermarket and walkability were
positively associated with physical health HRQoL (SF-36v2) measures,
while land-use mix, street connectivity, access to open and green space
and access to public transport were not significantly associated. Similar
associations were found for the mental health component, except for
population density with no significant association. Another study in
Bogotá, Columbia found neighbourhood (defined as 500 m-radius area)
characteristics, including public park density and transport infrastruc-
ture (presence of a Ciclovía corridor and number of TransMilenio sta-
tions) were not associated with either the physical or mental components of the HRQoL (SF-8) (Parra et al., 2010). However, those
who lived in neighbourhoods with >8 % of public park area were more
likely to have better self-rated health as assessed by the SF-8 than their
counterparts (Parra et al., 2010). In addition, previous studies have
found that neighbourhood-level SES was positively associated with the
physical component of versions of the short-form survey (Lucumí et al.,
2015; Tomey et al., 2013) yet mostly unrelated with the mental
component (Lucumí et al., 2015; Rocha et al., 2017; Tomey et al., 2013).

Given mental health and insomnia can affect HRQoL (Kennair et al.,
2022) as well as individuals’ perceptions of the environment (Gotlib &
Joormann, 2010; Leslie & Cerin, 2008), to establish if the neighbour-
hood environment impacts HRQoL, it is important that objectively
assessed, rather than perceived physical environmental factors, are
examined in associations with HRQoL (Zhang et al., 2019). The two
studies examining this issue have either focused on a limited number of
attributes (Parra et al., 2010), or have failed to account for potential
environmental confounders in the estimation of associations between
environmental attributes and HRQoL (Loo et al., 2017). To best under-
stand how neighbourhood environment factors impact HRQoL, capturing a wide range of inter-related environmental characteristics
(aspects of the built and natural environment, air pollution and SES) is
necessary, rather than focussing on one or a few.

Aspects of the built environment related to walkability (population/
dwelling density, street connectivity, access to various destinations and
services) are likely to be positively related to both physical and mental
components of HRQoL because they support an active lifestyle and
provide better access to health services and social activities (Loo et al.,
2017; Stier et al., 2021). Access to the natural environment can also
support active living (Barnett et al., 2017) and reduce stress (Gong et al.,
2016) and, hence, should enhance HRQoL, as suggested by Parra et al. (2010). Exposure to ambient air pollution is known to harm physical and
mental health (Fan et al., 2022; Hautekiet et al., 2022; Hu et al., 2021; Ju et al., 2022) and HRQoL (Hwang et al., 2020; Yamazaki et al.,
2005). Finally, as noted above, higher neighbourhood-level SES has been linked to better HRQoL (Ma & McGhee, 2013). Hence, in this study, we
expected it to be positively related to both physical and mental compo-
nents of the SFs.

The effects of the neighbourhood environment on HRQoL are distal
and, hence, statistical power to detect them is low (MacKinnon & Fair
child, 2009). Mediation analysis has greater power to detect links be-
tween the environment and HRQoL, as it estimates the associations
between the environment and more proximal constructs (e.g., physical
activity) that act as potential mechanisms through which the neigh-
bourhood environment impacts HRQoL. Studies have examined medi-
ators of exposure to HRQoL or environment-QL associations (e.g.,
Tomey et al., 2020; Zheng et al., in press). However, information on the
mediating roles of health-related behaviours, such as physical activity
and sedentary behaviours, is generally lacking. Physical activity and
sedentary behaviours are potential mechanisms responsible for the ef-
facts of the neighbourhood environment on HRQoL (Cerin et al., 2016)
because there is substantial evidence that some types of physical activity
(Barnett et al., 2017; Cerin et al., 2017; Van Cauwenberg et al., 2018)
and sedentary behaviours (Cerin, Barnett, et al., 2020) are influenced by

the neighbourhood environment in older adults, and physical activity
and sedentary behaviours have been found to be, respectively, positively
and negatively associated with HRQoL (Bertheussen et al., 2011; Brown
et al., 2003; Langhammer et al., 2018). A study on perceived environ-
ment and the mental component of the SF-36 found that self-reported
active transport and leisure-time physical activity explained 11 % of
the associations between the perceived neighbourhood physical activity
environment and mental HRQoL (Van Dyck et al., 2015). A recent study
of objectively assessed neighbourhood environment features and the
World Health Organization Quality-of-Life scale (WHOQoL) found that
physical activity was not a mediator of the associations between
neighbourhood environment features and physical and psychological
aspects of HRQoL (Zhang et al., in press). However, to our knowledge, it
seems no studies have examined the mediating role of different types of
physical activity and sedentary behaviours when examining associations
between objectively assessed aspects of the neighbourhood environment
and HRQoL as measured by the SF-36.

Based on the above, the aims of this study were 1) to examine the
associations between objectively assessed physical features of the
neighbourhood environment and physical and mental aspects of HRQoL
as measured by the SF-36, and 2) examine the mediating effects of
physical activity and sedentary behaviour in these associations. In doing
so, we took into consideration the potential causal relationships between
the various environmental attributes and behaviours (Cerin, Van Dyck,
et al., 2020), which is important to estimate total, mediated and direct
effects of the environment on HRQoL, and which has not been previ-
ously done.

As depicted in our proposed model of neighbourhood environment
influences on HRQoL (Fig. 1), we hypothesised that aspects of the built
environment related to walkability (population density, street connec-
tivity, access to various destinations and services) would be positively
related to both physical and mental components of HRQoL, because they
support an active lifestyle (i.e., more physical activity and less sedentary
time) and provide better access to health services and social activities
(Loo et al., 2017; Stier et al., 2021).

Access to the natural environment may also support active living
(Barnett et al., 2017) and reduce stress (Gong et al., 2016) and, hence,
be positively related to HRQoL. Because exposure to ambient air pollution
is known to harm physical and mental health (Braithwaite et al., 2019;
Fan et al., 2022; Hautekiet et al., 2022; Hu et al., 2021; Ju et al., 2022)
and HRQoL (Hwang et al., 2020; Yamazaki et al., 2005), negative asso-
ciations were expected between these factors. Finally, as noted above,
higher neighbourhood-level SES has been linked to better HRQoL (Ma &
McGhee, 2013). Hence, in this study, we expected SES to be positively
related to both physical and mental components of HRQoL. We also
hypothesised that most of the associations of the environment with
HRQoL would be indirect and explained by physical activity and
sedentary behaviours for the reasons mentioned above.

2. Materials and methods

2.1. Study design and participants

This study used data taken from the Australian Diabetes, Obesity and
Lifestyle survey (AusDiab3, conducted in 2011-12), a population based
longitudinal survey designed to examine prevalence, incidence, and
determinants of diabetes in Australians 25 years and older (Dunstan
et al., 2002; Tanamas et al., 2013). The third wave (AusDiab3) was
chosen for the present cross-sectional analyses as it was the only wave of
AusDiab with available relevant objectively-assessed environmental
exposures (e.g., air pollution and built environment attributes). Aus-
Diab3 retention rate from baseline was 44.6 % and over 97 % of par-
ticipants were aged >40 years. Participant eligibility required having no
major physical or intellectual disabilities, being in the target age bracket
and having lived at their addresses for 6 months or longer prior to the
survey. Compared to those who dropped out of the study, AusDiab3

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participants were younger \((p < .001)\), more physically active \((p < .01)\), less likely to smoke \((p < .01)\) and had higher education attainment levels \((p < .001)\) at baseline. As this study focussed on potential effects of urban neighbourhood environments of HRQoL, 473 participants who resided outside of significant urban areas were excluded from analysis, leaving an analytical sample of 4141 participants (2286 women and 1855 men) recruited from 1286 Statistical Areas 1 (SA1). With such a sample size, it was estimated that the study had 95 % power to detect small effect sizes equivalent to 1.0 % of explained outcome variance, assuming an SA1-level residual clustering effect <5 % (Cerin et al., 2016), up to 30 covariates in the regression models, and a 5 % 2-tailed significance level. The AusDiab study was approved by the Alfred Hospital Ethics Committee, Melbourne, Australia (ref. no 39/11). Participants were recruited from metropolitan and regional cities throughout Australia. Interviewer-administered surveys in English were used to collect data on HRQoL, health, health-related behaviours and sociodemographic characteristics. Written informed consent was obtained from all participants. Details of AusDiab data collection procedures are provided elsewhere (Anstey et al., 2015; Dunstan et al., 2002; Tanamas et al., 2013).

2.2. Measures

2.2.1. Health-related quality of life (outcomes)

The outcome measures were the Physical Component Summary (PCS) and Mental Component Summary (MCS) scores of the Short Form 36 Health Survey (SF-36 (v1)), a self-administered HRQoL measure (Ware, 2000). The component summaries were determined by three steps: 1) standardising the eight SF-36 scales using a Z-score transformation; 2) aggregating the Z-scores using the Australian Bureau of Statistics 1995 National Health Survey factor score coefficients as weights; and 3) transforming the aggregated summary scores to have a mean of 50 and standard deviation of 10 (Australian Bureau of Statistics, 1997). The structural validity and internal consistency of the eight SF-36 scales were confirmed in an Australian middle-to-old age adult sample of 41,338 participants aged 45–97 years (Bartsch et al., 2011). In the present study, the internal consistency coefficients (Cronbach’s α) of the PCS and MCS were 0.843 and 0.842, respectively.

2.2.2. Environmental measures (exposures)

ArcGIS v.10.5 (ESRI, Redlands) was used to generate neighbourhood built and natural environmental measures. Untrimmed street-network buffers of 1-km radius were created. A 1-km radius corresponds to the distance adults and older adults without mobility difficulties can walk in 10–20 min (Adams et al., 2014), and the neighbourhood has been commonly defined by a 20 min walk from home (Cerin et al., 2013; Gunn et al., 2017).

Further details on all the neighbourhood environmental exposures are available elsewhere (Cerin et al., 2021, 2023; Barnett et al., 2022; Cerin et al., 2022). Briefly, four built environment and two natural environment measures were computed for each participant’s residential buffer. These were population density (persons/hectare), street intersection density (intersections/km²), percentage of buffer area devoted to commercial land use, non-commercial land use mix (an entropy measure ranging from 0 to 1 and based on residential, medical, industrial, educational and other land use data) (Frank et al., 2010), percentage of parkland and percentage of blue space (i.e., water body areas). Two ambient air pollutants were estimated using validated national-scale satellite-based land-use regression models for annual average nitrogen dioxide \((\text{NO}_2, \text{ppb})\) and fine particulate matter \((\text{PM}_{2.5}, \text{μg/m}^3)\) (Knibbs et al., 2014, 2016, 2018). Neighbourhood SES was based on the Index of Relative Socio-economic Advantage and Disadvantage (IRSAD) (Australian Bureau of Statistics, 2011b) including information on household income, education, employment and marital status, occupational class, living arrangements, home and car ownership, housing conditions, internet access, disability, mortgage and rental costs. Sources for the above GIS data were the Australian Bureau of Statistics Mesh Block data from the 2011 Census (Australian Bureau of Statistics, 2011a), the PSMA Australia’s 2012 Transport & Topography dataset (PSMA Australia Ltd.,
and the national topographic spatial data for surface water features from Geoscience Australia (Crossman & Li, 2015).

2.3. Confounders and covariates

Information on confounders and covariates was collected using a self-completed survey. These variables were age, sex, educational attainment (up to secondary; trade, technician certificate; associate diploma or equivalent; Bachelor degree, post-graduate diploma), living arrangements (living alone; couple without children; couple with children; one person living with children; shared household; other arrangements), household annual income (up to $49,999; $50,000–$99,999; $100,000 and over; does not know or refusal), employment status (paid work; volunteer; neither), ethnicity (English speaking background: Yes vs. No) and residential self-selection (related to access to destinations and recreational facilities) (Cerin et al., 2021; Owen et al., 2007). For analyses purposes, the living arrangements categories one person living with children, shared household and other arrangements were collapsed due to low frequencies.

2.4. Mediators

We hypothesised that physical activity and sedentary behaviours may be potential mediators of the effects of the neighbourhood environment on HRQoL (Siceloff et al., 2014; Van Dyck et al., 2015). For this study, we used items adapted from Australian Institute of Health and Welfare (2003) measuring last-week frequencies of walking for transport, walking for recreation, vigorous gardening and resistance training. Examined sedentary behaviour mediators were last-week sitting for transport (hours/day) and leisure-time sitting (hours/day), which were developed for AusDiab3. These sedentary behaviour measures were validated against objectively measured sitting time (Clark et al., 2015). In this study, leisure time sitting included television viewing and leisure-time computer time.

2.5. Data analytic plan

Descriptive statistics, including percentage of missing values, were computed for all variables and presented in tabular form. Cross-sectional total, direct and indirect effects of neighbourhood environment attributes on HRQoL were estimated using generalised additive mixed models (GAMMs; package ‘mgcv’ version 1.8.22 (Wood, 2017) in R) with random intercepts at the SA1 level (Wood, 2017). As this is a cross-sectional study, the term ‘effect’, used in mediation analyses, does not imply evidence of causation and needs to be interpreted with caution considering the likely presence of unmeasured confounders. Minimal sufficient sets of confounders for the GAMMs estimating exposure-outcome, exposure-mediators and mediators-outcome relationships were determined using a directed acyclic graph (DAG) (Textor et al., 2016) (Fig. S1), which was based on published evidence and the authors’ expert opinion on causal effects among the variables. Potential multicollinearity was assessed by computing the Variance Inflation Factor (VIF) for each variable included in the GAMMs. All VIFs were smaller than 3, indicating no collinearity issues (Sheather, 2009). To test aspects of the proposed model of neighbourhood environmental influences on HRQoL (Fig. 1), analyses were conducted in several steps. First, the total effects of environmental attributes on the two components of HRQoL were estimated. In doing so, the curvilinearity of associations were also tested by comparing the Akaiake Information Criteria (AIC) values of GAMMs with linear vs. curvilinear regression terms (smooth terms) for each environmental attribute. A 5 unit or larger difference in AIC values (smaller AIC for the GAMM with a smooth term) was considered sufficient evidence of curvilinearity. Then the direct and mediated effects of the environmental attributes on HRQoL were estimated, i.e., the extent to which the effects of an environmental attribute on HRQoL were explained (i.e., mediated) by physical activity and sedentary behaviours. This included the estimation of confounder-adjusted associations of: (1) a specific environmental attribute with other environmental attributes in the pathway between the specific attribute and HRQoL (not reported as published elsewhere; Cerin et al., 2021); (2) environmental attributes with physical activity and sedentary behaviour measures; (3) physical activity with sedentary behaviour measures; and (4) physical activity and sedentary behaviour measures with HRQoL. The joint-significance test was used to establish mediation, whereby a variable is considered to be a mediator if it is significantly related to the exposure as well as the outcome after adjustment for the exposure (MacKinnon et al., 2002). Detailed information about the models is given in the Supplementary Material (Tables S1–S7). Estimates of total and direct effects of all neighbourhood environmental attributes on HRQoL were presented in tabular form. Statistically significant total, direct and behaviour-mediated effects of environmental attributes on HRQoL were also presented graphically as a simplified path diagram.

Over 16% of cases had missing data on at least one variable and data were at least missing at random (see Supplementary Material). Consequently, 20 imputed datasets were created for the regression analysis as recommended by Ruhen (1987) and van Buuren (2018). Multiple imputations by chained equations were performed using the package ‘mice’ (Van Buuren & Groothuis-Oudshoorn, 2011) in R version 4.0.0 (R Core Team, 2020). Analyses were conducted on multiple imputed data as well as on complete cases. As the findings between the two sets of analyses did not differ substantially, we report only those conducted on multiple imputed data. The complete case analyses are available on request from the corresponding author.

3. Results

Table 1 reports the sample descriptive statistics. Participants’ mean age was 61.1 years with a range from 34 to 97 years. Females comprised 55% of the sample. Educational attainment and annual household income categories were relatively evenly spread. In terms of HRQoL, the averages of both PCS (48.3 ± 8.9) and MCS (53.4 ± 9.7) T-scores were close to adult population averages (i.e., T-score of 50). However, the MCS tended to be higher than PCS. With regard to physical activity, leisure-time walking and resistance training were the activities with the highest and lowest rate of participation, respectively. On average, participants tended to accumulate fewer hours of sitting for transport than for leisure or other purposes (Table 1).

Table 2 reports the total and direct effects of neighbourhood environmental characteristics on HRQoL. Neighbourhood SES (IRSAD) and annual average PM2.5 concentrations showed significant positive and negative total and direct effects respectively on the physical component of HRQoL (Table 2). No other significant total or direct associations were observed.

Mediation analyses identified a substantial number of indirect effects of all examined neighbourhood environment attributes on both components of HRQoL through various physical activity measures and sitting for leisure but not sitting for transport (Fig. 2; Tables S9–S14). When controlling for environmental confounders, neighbourhood SES showed positive indirect effects on both components of HRQoL via resistance training and sitting for leisure. Data suggested that residents of higher SES areas were more likely to engage in resistance training and, consequently, sit less for leisure. Less sitting for leisure was, in turn, positively related to both HRQoL components. Furthermore, neighbourhood SES was negatively related to frequency of resistance training in those who engaged in this activity which, in turn, was associated with more sitting for leisure. This pathway also had a positive indirect effect on HRQoL due to sitting for leisure being negatively associated with both HRQoL components. Notably, the negative total effect of neighbourhood SES on sitting for leisure was fully explained by engagement in resistance training, as evidenced by the lack of a statistically significant direct effect.

Population density showed negative and positive indirect effects on
### Table 1: Participant and Neighbourhood Environment Characteristics (N = 4141).

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Statistics</th>
<th>Characteristics</th>
<th>Statistics</th>
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<tbody>
<tr>
<td><strong>Socio-demographic and other individual and household characteristics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age, years, M ± SD</td>
<td>61.1 ± 11.4</td>
<td>Sex, female, %</td>
<td>55.2 %</td>
</tr>
<tr>
<td>Educational attainment, %</td>
<td></td>
<td>Smoking history, %</td>
<td></td>
</tr>
<tr>
<td>Up to secondary</td>
<td>32.7 %</td>
<td>Current smoker</td>
<td>7.9 %</td>
</tr>
<tr>
<td>Trade, technician certificate</td>
<td>29.1 %</td>
<td>Previous smoker</td>
<td>35.9 %</td>
</tr>
<tr>
<td>Associate diploma &amp; equivalent</td>
<td>14.5 %</td>
<td>Non-smoker</td>
<td>54.5 %</td>
</tr>
<tr>
<td>Bachelor degree, post-graduate diploma</td>
<td>23.1 %</td>
<td>Missing data</td>
<td>2.6 %</td>
</tr>
<tr>
<td>Missing data</td>
<td>0.6 %</td>
<td>Household income, annual, %</td>
<td></td>
</tr>
<tr>
<td>Living arrangements, %</td>
<td></td>
<td>Up to $49,999</td>
<td>32.9 %</td>
</tr>
<tr>
<td>Couple without children</td>
<td>48.2 %</td>
<td>$50,000-$99,999</td>
<td>26.8 %</td>
</tr>
<tr>
<td>Couple with children</td>
<td>26.8 %</td>
<td>$100,000 and over</td>
<td>28.9 %</td>
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<tr>
<td>Other</td>
<td>22.4 %</td>
<td>Does not know or refusal</td>
<td>8.8 %</td>
</tr>
<tr>
<td>Missing data</td>
<td>2.5 %</td>
<td>Missing data</td>
<td>2.7 %</td>
</tr>
<tr>
<td>Residential self-selection – access to destinations, M ± SD</td>
<td>2.9 ± 1.3</td>
<td>Residential self-selection – access to recreational facilities, M ± SD</td>
<td>3.1 ± 1.5</td>
</tr>
<tr>
<td>Missing data</td>
<td>7.8 %</td>
<td>Missing data</td>
<td>7.8 %</td>
</tr>
<tr>
<td>Work or volunteer, %</td>
<td></td>
<td>English speaking background, %</td>
<td>89.9 %</td>
</tr>
<tr>
<td>Neither</td>
<td>30.4 %</td>
<td></td>
<td></td>
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<tr>
<td>Paid work</td>
<td>52.2 %</td>
<td></td>
<td></td>
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<tr>
<td>Volunteer</td>
<td>15.1 %</td>
<td></td>
<td></td>
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<tr>
<td>Missing data</td>
<td>2.3 %</td>
<td></td>
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</table>

| **Neighbourhood environment characteristics, M ± SD** |            |                                            |            |
| Neighbourhood SES                                    | 6.4 ± 2.7  | % Blue space (1 km buffer)                | 0.2 ± 2.0  |
| (IRSD, range 1–10)                                   |            |                                            |            |
| % Commercial land (1 km buffer)                       | 2.5 ± 6.1  | % Parkland (1 km buffer)                  | 11.6 ± 12.5|
| Population density (/ha)                             | 17.4 ± 10.0| Land use mix (entropy score)              | 0.35 ± 0.16|
| Air pollution - NO (ppb)                              | 5.5 ± 2.1  | Street intersection density (/km²)         | 62.2 ± 22   |
| Air pollution - PM₂.₅ (μg/m³)                         | 6.3 ± 1.7  |                                            |            |

| **Physical activity and sedentary behaviour**         |            |                                            |            |
| Transportation walking                                |            | Leisure-time walking                       |            |
| Times per week, M ± SD                               | 1.4 ± 3.5  | Times per week, M ± SD                     | 2.4 ± 2.5  |
| Prevalence, %                                        | 29.1 %     | Prevalence, %                              | 61.6 %     |
| Missing data, %                                      | 2.7 %      | Missing data, %                            | 3.0 %      |
| Vigorous gardening                                   |            | Resistance training                        |            |
| Times per week, M ± SD                               | 0.8 ± 1.5  | Times per week, M ± SD                     | 0.9 ± 2.3  |
| Prevalence, %                                        | 37.1 %     | Prevalence, %                              | 25.5 %     |
| Missing data, %                                      | 2.6 %      | Missing data, %                            | 2.6 %      |
| Sitting for transport, h/day, M ± SD                 | 0.8 ± 0.8  | Leisure-time sitting, h/day, M ± SD        | 2.6 ± 1.6  |
| Sitting (other purposes), h/day, M ± SD              | 3.4 ± 2.4  | Missing data, %                            | 2.8 %      |
| Health-related variables                             |            |                                            |            |
| Tobacco-smoking status, %                            |            | Heart problems/stroke (past), %           | 8.7        |
| % Current smoker                                     | 7.0 %      | Missing data, %                            | 1.0        |
| Previous smoker                                      | 35.9 %     |                                            |            |
| Non-smoker                                           | 54.5 %     |                                            |            |
| Missing data                                         | 2.6 %      |                                            |            |
| Health related quality of life outcomes               |            |                                            |            |
| SF36 - Physical Component Score (T-Score)            | 48.3 ± 8.9 | SF36 - Mental Component Score (T-Score)    | 53.4 ± 9.7 |
| Missing data                                         | 0.1 %      | Missing data                               | 0.1 %      |

**Note.** M, mean; SD, standard deviation; SES, socio-economic status; IRSAD, Index of Relative Socio-economic Advantage and Disadvantage; ha, hectare; NO₂, nitrogen dioxide; ppb, particles per billion; PM₂.₅, particulate matter with a diameter of 2.5 μm or less.

* Land use mix includes residential, medical, educational, industrial and other land uses. It is expressed as an entropy score ranging from 0 to 1.

Both HRQoL components through different pathways. Positive indirect effects were observed through engagement in resistance training and walking for transport because these two activities were positively related to population density as well as negatively related to sitting for leisure (which was likely detrimental to HRQoL) (Fig. 2). While the total and direct effects of population density on resistance training were similar (Fig. 2; Table S9), those related to walking for transport differed substantially (Fig. 2; Table S10), indicating that the positive association of population density with walking for transport, but not that with resistance training, may be due to environmental factors accompanying densification (i.e., availability of commercial destinations, better street connectivity, more mixed land use). The negative indirect effects of population density were channelled through frequency of vigorous gardening/yard work and sitting for leisure. This is because, after adjusting for physical activity, population density was positively related to sitting for leisure. Furthermore, population density was negatively related to frequency of vigorous gardening/yard work which, in turn, was negatively related to sitting for leisure. As for walking for transport, the total effect of population density on gardening/yard work was fully accounted for by other environmental attributes resulting from densification as no significant direct effect was observed (Fig. 2; Table S12).

Street intersection density also displayed contrasting indirect effects, two of which were also via engagement in walking for transport and frequency of vigorous gardening/yard work. A third pathway emerged through engagement in walking for recreation, which was positively related to the PCS directly and to PCS and MCS indirectly through sitting for leisure. The remaining built environment features showed consistent indirect effects on HRQoL. Percentage of commercial land use displayed positive indirect effects on both HRQoL components via engagement in walking for transport and vigorous gardening/yard work frequency through sitting for leisure. In contrast, non-commercial land use mix had a negative indirect effect on HRQoL via gardening/yard work frequency. Specifically, this environmental measure was negatively related to gardening/yard work frequency, which was, in turn, negatively related to sitting for leisure contributing to poorer HRQoL. The negative total effect of non-commercial land on gardening/yard work frequency was explained by other environmental attributes in the pathway (air pollution) as the direct effect was not statistically significant (Fig. 2; Table S12).

Both percentage of parkland and percentage of blue space displayed positive and negative indirect effects on HRQoL. For parkland, the former were channelled through engagement in resistance training and sitting for leisure, while the latter were channelled through engagement in walking for recreation and sitting for leisure. For percentage of blue space, the positive indirect effect was due to this environmental attribute being negatively related to sitting for leisure, while negative effects were due to the negative associations of the neighbourhood attribute with engagement in walking for transport and frequency of vigorous gardening/yard work which were, in turn, negatively related to sitting for leisure.

Finally, positive indirect effects on HRQoL were found for both air pollution indicators (NO₂ and PM₂.₅). These were due to them being positively related to engagement in walking for transport, which was negatively associated with sitting for leisure, and the latter negatively associated with both components of HRQoL. The fact that PM₂.₅ showed a significant negative total effect but non-significant direct effect on sitting for leisure, after adjustment for engagement in walking for transport (Fig. 2), indicates that walking for transport mediated in full the association between PM₂.₅ and sitting for leisure.
4. Discussion

The purpose of this study was to examine the validity of a model of neighbourhood environmental correlates of HRQoL by estimating associations of neighbourhood physical attributes and SES with HRQoL and the mediating roles of physical activity and sedentary behaviour in

### Table 2

<table>
<thead>
<tr>
<th>Environmental characteristic (units)</th>
<th>Effect</th>
<th>Physical component score (HRQoL)</th>
<th>Mental component score (HRQoL)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b</td>
<td>95% CI p-Value</td>
<td>b</td>
</tr>
<tr>
<td>Population density (persons/ha)</td>
<td>Total</td>
<td>0.004 -0.032, 0.025 0.812</td>
<td>-0.023 -0.055, 0.010 0.167</td>
</tr>
<tr>
<td></td>
<td>Direct</td>
<td>-0.004 -0.046, 0.038 0.856</td>
<td>-0.030 -0.079, 0.018 0.220</td>
</tr>
<tr>
<td>Street intersection density (intersections/km²)</td>
<td>Total</td>
<td>0.0004 -0.010, 0.011 0.947</td>
<td>0.003 -0.009, 0.015 0.603</td>
</tr>
<tr>
<td></td>
<td>Direct</td>
<td>-0.002 -0.009, 0.013 0.746</td>
<td>0.004 -0.009, 0.016 0.577</td>
</tr>
<tr>
<td>Percentage of commercial land use</td>
<td>Total</td>
<td>-0.003 -0.049, 0.042 0.885</td>
<td>0.009 -0.044, 0.063 0.733</td>
</tr>
<tr>
<td></td>
<td>Direct</td>
<td>-0.002 -0.049, 0.043 0.902</td>
<td>0.026 -0.042, 0.020 0.358</td>
</tr>
<tr>
<td>Non-commercial land use mix (entropy score)</td>
<td>Total</td>
<td>0.365 -1.482, 2.213 0.699</td>
<td>-0.921 -2.987, 1.144 0.382</td>
</tr>
<tr>
<td></td>
<td>Direct</td>
<td>1.008 -1.101, 3.116 0.349</td>
<td>-0.427 -2.871, 2.016 0.732</td>
</tr>
<tr>
<td>Percentage of parkland</td>
<td>Total</td>
<td>0.009 -0.017, 0.035 0.496</td>
<td>-0.010 -0.041, 0.020 0.506</td>
</tr>
<tr>
<td></td>
<td>Direct</td>
<td>-0.002 -0.027, 0.0238 0.888</td>
<td>-0.011 -0.042, 0.020 0.492</td>
</tr>
<tr>
<td>Percentage of blue space</td>
<td>Total</td>
<td>0.052 -0.081, 0.186 0.444</td>
<td>0.060 -0.094, 0.215 0.445</td>
</tr>
<tr>
<td></td>
<td>Direct</td>
<td>0.039 -0.101, 0.161 0.655</td>
<td>0.037 -0.116, 0.190 0.637</td>
</tr>
<tr>
<td>Neighbourhood SES (IRSAD)</td>
<td>Total</td>
<td>0.202 0.092, 0.312 &lt;0.001</td>
<td>0.049 -0.079, 0.177 0.455</td>
</tr>
<tr>
<td></td>
<td>Direct</td>
<td>0.175 0.059, 0.292 0.003</td>
<td>0.037 -0.099, 0.172 0.597</td>
</tr>
<tr>
<td>Air pollution - NO₂ (ppb)</td>
<td>Total</td>
<td>0.015 -0.169, 0.199 0.869</td>
<td>-0.040 -0.249, 0.169 0.707</td>
</tr>
<tr>
<td></td>
<td>Direct</td>
<td>0.024 -0.160, 0.207 0.801</td>
<td>0.013 -0.200, 0.225 0.907</td>
</tr>
<tr>
<td>Air pollution - PM₂.₅ (μg/m³)</td>
<td>Total</td>
<td>-0.218 -0.393, -0.044 0.014</td>
<td>-0.050 -0.257, 0.157 0.639</td>
</tr>
<tr>
<td></td>
<td>Direct</td>
<td>-0.223 -0.398, -0.048 0.012</td>
<td>-0.035 -0.241, 0.172 0.743</td>
</tr>
</tbody>
</table>

**Note.** Physical and Mental Component Scores (T-Score) as derived from the SF-36; ha, hectare; IRSAD, Index of Relative Socio-economic Advantage and Disadvantage; ppb, particles per billion; NO₂, air pollution nitrogen dioxide; ppb, particles per billion; PM₂.₅, particulate matter with a diameter of 2.5 μm or less; b, regression coefficient; CI, confidence intervals. Associations significant at the 0.05 probability level are in bold. Covariates entered in the regression models are reported in Table S1 (Supplementary Material).

a Non-commercial land use mix includes residential, medical, educational, industrial and other land uses; the indicator is expressed as an entropy score ranging from 0 to 1.

Fig. 2. Indirect effects of neighbourhood environmental attributes on the physical (PCS) and mental components (MCS) of health-related quality of life (SF-36). Subscript T = estimate of total effect, subscript D = estimate of direct effect, b = regression coefficient, e^b = exponentiated regression coefficient, OR = odds ratio. Res Train Freq = Resistance training frequency, Res Train Y/N = Engagement in resistance training, Walk Rec Y/N = Engagement in walking for recreation, Walk Trans Y/N = Engagement in walking for transport, Gardening Freq = Vigorous gardening/yard work frequency, Leisure sitting = Sitting for leisure, *p < .05, **p < .01, ***p < .001.

4. Discussion

The purpose of this study was to examine the validity of a model of
these associations in a cohort of Australian mid-aged and older adults. While only PM2.5 and neighbourhood SES (IRSAD) showed significant total and direct associations with PCS, all environmental attributes were indirectly significantly associated with HRQoL via sitting for leisure and/or physical activity. The lack of total and direct associations can be attributed to some environmental attributes having contrasting effects on different domains of physical activity (e.g., parkland being positively associated with resistance training and negatively associated with leisure-time walking) or environmental attributes being distal influencing factors with respect to HRQoL (e.g., street intersection density). The data generally supported the validity of the proposed model, although the hypothesised associations were not always in the expected direction. These findings are discussed in detail below.

4.1. Neighbourhood SES

Neighbourhood SES was the only neighbourhood attribute that showed a total and direct positive association with HRQoL, and only with PCS (Table 2). As noted earlier, prior studies have also found that neighbourhood-level SES was positively associated with the physical component of versions of the SF (Lucumi et al., 2015; Tomy et al., 2013) and mostly unrelated with the mental component (Lucumi et al., 2015; Rocha et al., 2017; Tomy et al., 2013). People living in lower SES neighbourhoods typically have poorer physical health as well as poorer perceptions of the same, irrespective of their health status (Rocha et al., 2017). Disadvantaged neighbourhoods may also lack facilities, services and social norms promoting a healthy lifestyle (Macintyre et al., 2002; Pickett & Pearl, 2001).

The reason for not finding a significant total or direct effect between neighbourhood SES and the MCS is unclear. However, in the current study, neighbourhood SES was indirectly, positively associated with both HRQoL components via resistance training and sitting for leisure (Fig. 2). Mid-aged and older adults tend to accumulate sitting for leisure mainly through TV viewing (Compernolle et al., 2021), which has been associated with poor physical and mental health (Compernolle et al., 2021; Gardner et al., 2014) and lower individual-level (Gardner et al., 2014) and neighbourhood-level SES (Coogan et al., 2012). This study also suggests that some of the time spent sitting for leisure (e.g., TV viewing) can be potentially displaced by leisure-time physical activity (Gardner et al., 2014) and this may benefit both physical and mental health. Furthermore, we found that participation in resistance training may directly benefit the physical component of HRQoL, i.e., irrespective of its effects on PCS via sitting for leisure. Resistance training improves muscle strength and the capacity to perform activities of daily living, which are likely to improve HRQoL (Hart & Buck, 2019; Levinger et al., 2007).

Interestingly, while, in our study, participants from higher SES areas were more likely to partake in resistance training, they were less likely to undertake it frequently, which was somewhat unexpectedly associated with them having lower scores on the PCS. These findings were similar to those in a study of a nationally representative Australian adult sample (Freeston et al., 2017) which found that residents of more socially advantaged areas were more likely to participate in resistance training but, among those who participated in this type of activity, residents of less advantaged areas tended to have a higher weekly frequency of participation. Residents of higher SES areas may have access to and be interested and be able to afford participating in a greater variety of leisure-time physical activities compared to their counterparts who may only participate in one activity, such as resistance training (Kamphuis et al., 2008).

4.2. Neighbourhood built environment

Although no significant total or direct effects of neighbourhood built environment features on HRQoL were observed, all examined features were indirectly related to PCS and MCS via physical activity and leisure-time sitting. The indirect associations of population and street intersection density with HRQoL were inconsistent, while those of commercial land use and non-commercial land use mix were, respectively, positive and negative. Overall, our study suggests that urban design features that define neighbourhood walkability (density, access to services and street connectivity) are distal factors influencing HRQoL by promoting or hindering lifestyle behaviours that are beneficial (physical activity) or detrimental (sitting) to health. These complex and contrasting distal pathways of influence may explain why previous studies reported conflicting findings on built environmental correlates of HRQoL as measured by the SF (Loo et al., 2017; Parra et al., 2010). We discuss the specific findings of our study below.

As observed for neighbourhood SES, population density was indirectly positively related to both PCS and MCS via its positive association with engagement in resistance training, which was predictive of less leisure-time sitting. Dense neighbourhoods may encourage participation in resistance training because they provide more physical and social resources for such activities (e.g., indoor recreational facilities and fitness clubs/groups) (Cerin, Barnett, et al., 2020). However, unlike neighbourhood SES, population density was also directly positively associated with leisure-time sitting and, hence, showed negative effects on both PCS and MCS through this pathway. That population density can potentially promote as well as hinder an active lifestyle in ageing populations has been observed in recent studies. For example, Belgian older adults showed positive direct associations of residential density with both accelerometer-assessed moderate-to-vigorous physical activity and sedentary time (Cerin, Van Dyck, et al., 2020). This finding was attributed to more dense environments providing more opportunities for incidental and structured physical activities in the neighbourhood and, at the same time, fewer opportunities for household and gardening activities due to the smaller size of dwellings and the lack of private gardens (Cerin, Van Dyck, et al., 2020).

Unsurprisingly, population density, as well as street intersection density and percentage of commercial land use, were positively associated with both PCS and MCS via engagement in walking for transport and leisure-time sitting. The various operationalisations of these environmental attributes that have been used to define neighbourhood walkability indices (Cerin et al., 2010; Frank et al., 2010; Leslie et al., 2007) showed consistent positive associations with older adults’ walking for transport (Cerin et al., 2017). Engagement in walking for transport, as a proxy for engagement in various activities in the neighbouring area, may displace some TV viewing and other home-based leisure-time sedentary activities. In fact, a longitudinal study conducted in Belgian mid-aged and older adults reported that declines in active transport were accompanied by increases in leisure-time sitting (Van Dyck et al., 2016).

One of the neighbourhood walkability components included in this study – street intersection density was also positively related to HRQoL through engagement in recreational walking which, in turn, was directly positively associated with PCS and indirectly associated with both HRQoL components through leisure-time sitting. The observed association between this environmental feature and walking for recreation is in line with the findings of a systematic review and meta-analysis on environmental correlates of leisure-time physical activity in older adults (Van Cauwenberg et al., 2018), suggesting that street intersection density may promote walking for recreation in ageing populations by providing easy access to places for socialising and other various facilities in the neighbourhood. As to the positive associations between walking for recreation and aspects of HRQoL, they have been reported in many studies (Han et al., 2021). However, these studies did not investigate the mediating role of leisure-time sitting.

Neighbourhood walkability features, including population density, street intersection density and non-commercial land use mix, were also indirectly negatively associated with HRQoL via frequency of vigorous gardening and leisure-time sitting. As dense urban environments with mixed land use are likely to have small or no gardens, it is not surprising
that their residents report minimal or no vigorous gardening/yard work. It is also not surprising that minimal or no participation in gardening resulted in more sitting for leisure in this older demographic. However, the positive, albeit weak, association of commercial land use with gardening frequency found in the present study was not expected because areas with a high prevalence of commercial facilities typically do not have gardens.

4.3. Neighbourhood natural environment

Despite the inconsistent findings in the literature (Loo et al., 2017; Parra et al., 2010), we hypothesised that access to parkland would be associated with better HRQoL directly (e.g., by reducing stress) and indirectly (by promoting leisure-time physical activity). Our hypotheses were only partially confirmed. Specifically, parkland was indirectly, positively associated with PCS via engagement in resistance training, but, in contrast, was indirectly, negatively associated with PCS via engagement in walking for recreation (with and without mediation by leisure-time sitting). A recent systematic review on the impact of types of physical activity in green urban space on adult health and behaviours (Grigoletto et al., 2021) noted that, worldwide, an increasing number of parks have outdoor fitness equipment. This may explain the observed link between parkland and engagement in resistance training. The negative association between parkland and recreational walking is more puzzling. In their systematic review and meta-analysis, Van Cauwenberg and colleagues reported a positive association between parks/open spaces and overall leisure-time physical activity rather than walking for recreation in older adults (Van Cauwenberg et al., 2018). They also noted that access to services was the strongest environmental correlate of walking for recreation. Older adults may prefer walking in safe areas with good visibility and tend to avoid isolated trails in parks (Moran et al., 2014). If percentage of parkland in a neighbourhood is a proxy for lack of visibility and isolation, it is not surprising that it was weakly negatively related to walking for recreation. Also, parks are only one of the common locations where older people walk for recreation (Barnett et al., 2015).

Blue space in the neighbourhood is the other natural environmental attribute examined in the present study. We hypothesised it would be positively related to HRQoL directly (by reducing stress) and through lifestyle behaviours (by promoting an active lifestyle) (White et al., 2020). As expected, blue space was indirectly positively associated with PCS and MCS via its negative association with sitting for leisure. However, it was indirectly negatively associated with both components of HRQoL via its negative associations with walking for transport and vigorous gardening frequency. These findings may be in part due to the way access to blue space was operationalised. A high percentage of blue space in a 1-km buffer around a residential address implies that there is less space for other land uses, such as commercial or residential. This would result in a negative association of this particular measure of blue space with walking for transport as well as gardening. Recent studies that examined the relationship between blue space and HRQoL and similar constructs tended to use distance to blue space and blue space use as exposures. For example, in Ireland, people living within 2 km of blue spaces reported significantly more life satisfaction than people living further than 5 km away (Brereton et al., 2008). Subsequent research in Canada (Pearson et al., 2019), China (Helbich et al., 2019), England (Alcock et al., 2020; Garrett, Clitheroe, et al., 2019) and the Netherlands (De Vries et al., 2016) found living near the coast or inland water bodies was associated with better mental health. With regard to PCS and MCS (SF-12v2), blue space use in two German cities was a better indicator of health outcomes than perceived walking distance to the blue space (Volker et al., 2016). Furthermore, a study of Hong Kong (mainly older) residents found that those with a view of blue space from home were more likely to report good general health, while intentional exposure was linked to greater odds of high wellbeing (Garrett, White, et al., 2019).

4.4. Air pollution

Average annual PM_{2.5} concentrations were negatively associated with PCS but not MCS in the total and direct effect models. This was not the case for NO_{2}, which was unrelated to HRQoL. Surprisingly, both NO_{2} and PM_{2.5} were indirectly and positively associated with PCS and MCS via engagement in walking for transport and sitting for leisure. PM_{2.5} was also indirectly and positively associated with PCS and MCS via sitting for leisure only (Fig. 2). In contrast, a study in Belgium (Hautekiet et al., 2022) found that an interquartile range (IQR) increment of either PM_{2.5} or NO_{2} long-term exposure was associated with higher odds of poor self-rated health. Also, a recent study based on the multi-site European Community Respiratory Health survey found higher NO_{2}, PM_{2.5} and PM_{10} were associated with lower MCS (Boudier et al., 2022).

The difference between our findings and those from these European studies might be attributed to methodological differences in exposure assessment or the levels of air pollution in the two continents. The average annual concentrations of PM_{2.5} and NO_{2} in the present study were >50 % lower than those reported in Europe. For example, while the annual average concentration of PM_{2.5} in our study was 6.3 μg/m^3 in 2020, 96 % of the European Union urban population were exposed to levels of PM_{2.5} above the health-based guideline level set by the World Health Organization (European Environment Agency, 2022) which is 15 μg/m^3. It is possible that the levels and/or variability of PM_{2.5} and NO_{2} in our sample group is insufficient to have a clear effect on both components of HRQoL. Moreover, the positive associations of PM_{2.5} and NO_{2} with walking for transport suggest that, in our study, these measures might be proxies of access to destinations such as food outlets and retail, which were not accurately captured by our measures of access to services – namely, percentage of commercial land use and non-commercial land use mix. The same reasoning applies to the observed associations of these air pollutants with leisure-time sitting in the present study.

4.5. Strength and limitations

A strength of this study was the use of objective rather than perceived measures of the neighbourhood environment allowing a more robust assessment of potential causal relationships, given that perceptions of the environment and HRQoL are both influenced by poor mental health (Gottlieb and Joormann, 2011; Kennair et al., 2022; Leslie & Cerin, 2008; Zhang et al., 2019). Another strength was the use of DAGs to determine minimal sufficient sets of confounders for the regression models estimating exposure-outcome, exposure-mediators and mediators-outcome associations based on a theoretical model of neighbourhood environmental influences on HRQoL. That considered plausible causal effects among environmental attributes as well as lifestyle behaviours. Furthermore, this study accounted for neighbourhood self-selection by adjusting the regression models for physical activity-related reasons for living in a specific neighbourhood.

Study limitations include the cross-sectional nature of the available data, which limits the ability to estimate causal effects. The sample was not representative of the Australian urban population of mid-aged and older adults in terms of health because the third wave of AusDiab included relatively healthy individuals. Specifically, they were more physically active, less likely to smoke and more highly educated than those who dropped out from the study (Barnett et al., 2022; Cerin et al., 2021). This may have resulted in underestimated associations between environmental attributes and HRQoL. We relied on self-report measures of physical activity and sedentary behaviours which are known to be less accurate than device-based measures (Prince et al., 2020). Accuracy is especially a problem among people with cognitive difficulties, such as those arising from ageing-related cognitive decline (Shepard, 2003). These measures did not distinguish activities undertaken within the neighbourhood from those that were undertaken outside the neighbourhood of residence. Finally, the objective measures of access to a
5. Conclusions and practical implications

We examined neighbourhood environmental correlates of HRQoL as measured by the SF-36 and the mediating roles of physical activity and sedentary behaviours in a national sample of Australian mid-aged and older adults. Only neighbourhood SES and average annual PM$_{2.5}$ concentrations showed significant total and direct associations with PCS in the expected direction. All other environmental attributes were related to the physical and mental components of HRQoL via physical activity behaviours and leisure-time sitting. Most environmental features had both positive and negative associations with physical activity and/or sedentary behaviours leading to null total associations with HRQoL.

Overall, neighbourhood SES appears to have beneficial effects on HRQoL by helping promote an active lifestyle and through other mechanisms that were not captured in this study. Built environment attributes defining neighborhood walkability appear to have beneficial effects on HRQoL by promoting walking and resistance training and, through these, by helping decrease leisure-time sitting. However, some of these attributes may also lead to more sitting in mid-aged and older adults by limiting opportunities for household and gardening activities. Access to natural features may also promote some activities (e.g., resistance training, less sitting) and hinder others (gardening). These findings highlight the importance of examining the potential effects of the neighbourhood environment on the HRQoL through mediation analyses encompassing key inter-related neighbourhood environmental attributes (aspects of the built and natural environment and air pollution) and a variety of lifestyle behaviours theoretically linked to specific environmental features and HRQoL.

From an urban planning policy perspective, this study suggests that the creation of dense neighbourhoods typified by good access to commercial destinations and a well-connected street network may be beneficial to mid-aged and older adults' HRQoL by encouraging walking and participation in resistance training. The potentially negative effects of dense, walkable neighbourhoods on physical activity accrued through gardening appear to be limited in size and, probably, relevant to geographical contexts and cultures where gardening may contribute to a substantial amount of daily physical activity, such as Australia or the UK. The establishment of urban community gardens may help address this particular shortcoming of urban densification. That neighbourhood natural features (parkland and blue spaces) showed mixed associations with physical activity suggests that, to maximise their beneficial effects on HRQoL, they need to an integral part of dense, destination-rich neighbourhoods so that residents have a wide range of options that support an active lifestyle. Finally, our study suggests that urban planning and transportation policies that reduce ambient air pollution (e.g., establishment of low-emission zones, smart traffic lights, an efficient and affordable public transport network, urban gardens) are needed to enhance older residents’ HRQoL.

Declaration of competing interest

None.

Data availability

Data that support the findings of this study are available on request under a license agreement. Written applications can be made to the AusDiab Steering Committee (Dianna.Magliano@baker.edu.au).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cities.2023.104538.

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