Calculating a national Anomie Density Ratio: Measuring the patterns of loneliness and social isolation across the UK's residential density gradient using results from the UK Biobank study

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Highlights

- Examined associations of residential density with loneliness and social isolation.
- The study comprised N=405,925 UK Biobank cohort participants.
- Residential unit density measured within 1- and 2-Km residential street catchment.
- Residential density was associated with higher loneliness and social isolation.
- Density effect of terraced housing was beneficial while that of flats was opposite.

Abstract

Urban life has long been pilloried in history for its negative effects on the human condition and mind. From Thomas Jefferson to Emile Durkheim, high density urban living as an aberration to be rectified has been part of the modern discourse on cities. While empirical studies into the psychiatric effects of unwanted social contact began in earnest after WW2 and we now know much about environmental causes of stress, the evidence of the impacts of increasing urban densification upon loneliness and social isolation in humans still remains inconclusive. We employed high-resolution geospatial built environment exposure data to examine associations between residential density and loneliness and social isolation among 405,925 UK Biobank cohort participants. Residential unit density was measured within a 1- and 2-Km residential street network catchment of participant's geocoded dwelling. Other health-specific built environment (i.e., street-level physical walkability, density of public transport, traffic intensity of the nearest road, mean street distance to destinations), and physical environment exposures (terrain variability and greenspace exposure modelled from remotely-sensed data) were also measured at individual-level as attributes of each participant's geocoded dwelling. We found for the UK, that every 1,000 units/km^2 increment in residential density within a 1-Km network catchment was independently associated with a 2.8% (odds ratio: 1.028, $p=0.0058$) and 11.4% (OR: 1.114, $p<0.0001$) higher odds of loneliness and social isolation respectively. This can be interpreted as the density elasticity of loneliness (social isolation), which we coin as the *Anomie Density Ratio (ADR)*. In addition, with reference to the lowest density quartile, the fourth-quartile was associated with 14.4% and 30.4% higher odds of loneliness and social isolation respectively. The associations were slightly more pronounced at spatial scale of 2-Km, indicating the possibility of a scale effect in this emblematic urban-ill. Higher density of detached housing was negatively associated with both loneliness and social isolation, while density of flats was positively associated with both outcomes. More pronounced effects of residential density on loneliness were identified among males and those retired, while for social isolation, similar effect was observed among the retired. As far as we know, this is the first study to measure the density-loneliness effect using individual (non-ecological) data on a large national sample, controlling for personal confounders and mitigating environmental factors such as green space. Density was associated with loneliness and social isolation independently of other factors, which means that

urban design and density planning strategies matter; especially in an age of accelerating suburban densification.

***Keywords*:** Loneliness, social isolation, anomie, residential density, built environment, UK Biobank, UKBUMP.

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I have at last, after several months' experience, made up my mind that it is a splendid desert--a domed and steepled solitude, where the stranger is lonely in the midst of a million of his race. A man walks his tedious miles through the same interminable street every day, elbowing his way through a buzzing multitude of men, yet never seeing a familiar face, and never seeing a strange one the second time.

Mark Twain
Letter to San Francisco *Alta California, June 5, 1867*

1. Introduction

Being inherently social beings, connectivity and social contacts have always been fundamental to the sustenance of human health and wellbeing (House et al., 1988). In recent years, loneliness and social isolation have emerged as an epidemic posing massive health burdens (Cacioppo et al., 2015; Miller, 2011). They are also associated with higher risks of mental health disorders (Matthews et al., 2016). With a steadily ageing global population, the challenges posed by urban loneliness and social isolation have been exacerbated by the deleterious health effects in elderly population including cognitive decline (Boss et al., 2015; Shankar et al., 2013) and dementia (Kuiper et al., 2015). Elderly mental health conditions both exacerbate and are exacerbated by loneliness. Loneliness and social isolation also increase the risks of all-cause mortality (Elovainio et al., 2017), and coronary heart disease and stroke (Valtorta et al., 2016).

Since the first late Neolithic human settlements, there has been a multi-fold rise in urbanization, with 55% (4.2 billion people) of the global population currently residing in cities, and one in every three living in cities of at least half a million inhabitants (United Nations, 2016). Cities are clusters of people, infrastructure, technologies and services that evolve to deliver the shared benefits (positive externalities in economic terms) that drive population-wide prosperity and wellbeing (Hall, 1998). High density living is attractive for multiple reasons, being generally synonymous with convenient living, higher land use mix, higher concentration of service destinations, and higher economies of scale in consumption and production. More compact cities and neighbourhoods can mean shorter origin-destination trip lengths, lower commute times, a higher proportion of active travel, stronger cognitive maps of places, more opportunities for social interactions and greater sense of community, more defensible space, and more liveable places (Jacobs, 1961; Lynch, 1960; Newman, 1966). On the other hand, the phenomenon of densification in cities is inherently associated with significant social, economic and demographic transformations, which over time, interacts with resident's health. As a result, phases of so called epidemiological transition occur producing complex population-level disease patterns (mortality, chronic and infectious diseases) transitioning over time (Omram, 2001). Noteworthy to mention is the role of the 20th century's massive urbanization drives in delivering middle-income well-being to the masses, and at the same time producing shifts in disease patterns from infectious to chronic diseases of longer latencies and complex etiologies – the modern 'urban plagues'. Short and long term health costs are among the negative consequences of human co-location at high density. Other shared negative externalities relate to the high density impervious built-up spaces required to support the subsistence, betterment and interactions between citizens: congestion, pollution, commutes, crime, social dislocation, infectious disease risk, and the stresses and strains of sedentary lifestyles (Deweerdt, 2016; Sarkar and Webster, 2017).

The links between urbanization, loneliness and social isolation have long been discussed (Fischer, 1973). The serious study of social alienation, psychological stress, mental health and urban living conditions began in earnest after the Second World War (Peplau and Perlman, 1982). French sociologist Emile Durkheim had popularized the idea of urban anomie, a divergence between individual and social expectations, norms and goals that leads to economic, social and psychological pathology. Although *urban anomie* was not explicitly formulated as a theory of density, Durkheim and other influential social-psycho theorists saw the 'role strain' (Merton, 1938) experienced by urbanites as a result of the proximate living of many people from different backgrounds and value systems. Merton's and Durkheim's urban social stress was the flipside of the economists' division of labour. Indeed, before Durkheim proposed anomie as a theory of suicide, he had used the idea of anomie to investigate how shared values in craft guilds had hindered industrial progress in the 19th and early 20th century (Durkheim, 1933). This early sociological narrative remains influential but the growing body of epidemiological research on urbanicity and mental wellbeing rests on an individual level of analysis. Tensions between individual and social norms are difficult to measure in large-scale healthy city studies. Built environment attributes, including housing density, are more easily measured, however (if tediously). Our study hypothesizes measurable associations between the individual health outcomes of loneliness and isolation, and housing density as an environmental condition.

Regardless of underlying psycho-social theory, the way cities are designed and developed clearly has enduring effects on human social interactions. Urban living environments create or inhibit a sense of belonging; create less or more unwanted social interactions; may or may not create systems of shared norms to overcome anomie; and may inhibit or encourage lawlessness (Newman, 1972). There are various plausible reasons, therefore, for associating urban morphology, including density, with risks of loneliness, social isolation and other dependent downstream health outcomes, especially mental health and other chronic conditions. Hence, specific attributes of urban built environments that determine individual and population health, including psychosocial resources in a city, have become of increasing interest as cities and urban populations expand and urban health risks deepen (Boyden, 2004; Giles-Corti et al., 2016; Lederbogen et al., 2013).

The role of urban mental capital and individual mental health in creating inclusive, resilient and sustainable cities is acknowledged in the UN's Sustainable Development Goals (SDGs) framework. The Lancet Commission on Global Mental Health and Sustainable Development was set up to create a more holistic framework for Global Mental Health within the SDGs, stressing the importance of prevention and treatment of mental, neurological and substance-use disorders as well as specific policy focus on mental health promotion as reflected in SDG 3.4 (Patel et al., 2018). In pursuing the social determinants of mental health, there has been a focus on upstream-level factors, such as reducing inequality (SDG 10) as well as making cities and settlements safe, resilient and sustainable (SDG 11) (Lund et al., 2018). The UK Government's Foresight Project on Mental Capital and Wellbeing highlighted the importance of supporting urban neighbourhoods with appropriate physiological and psycho-social resources that enable mental capital and wellbeing to flourish over the life-course (Beddington et al., 2008). The importance of urban design and place making at neighbourhood- and city-scale in facilitating or obstructing social connections in cities has also been highlighted (Kelly et al., 2012). Urban mental health is now better understood than in Durkheim's day and with research questions that are more specific. With large-scale studies employing high resolution objectively measured built environment and individual health variables, we are now able to be a lot more precise about the science of urban anomie.

The role of residential density is of fundamental importance to urban health, as the COVID-19 pandemic in ultra-high density worker dormitories has re-emphasized (Koh, 2020). Residential density is a proxy for multiple phenomena related to urban-induced malaise, such as personal space deprivation, proximity to others, density of airborne toxins and pathogens, urban noise, traffic congestion, crime, night light and lack of greenery. Housing constitutes the basic building blocks of any city, and residential neighbourhoods shape the spatial and temporal patterns of nearly all activity- and lifestyle-influencing land uses and services. Consequently, the continuum of residential density and adjoining land uses in a city, govern urban activity-patterns and the quantity and quality of social connections.

In a seminal experimental study on rats, ethologist John Calhoun observed that increasing rat population density led to increasing frequency of unwanted social contacts, stress and aggression and eventual mortality and decline in the population (Calhoun, 1962). Similar observations have been corroborated in more recent animal studies conducted on mice and Japanese macaques, showing that increasing living density is correlated with social avoidance, with elevated concentrations of stress biomarkers (plasma cortisol and plasma corticosterone) (Lee et al., 2018). Recent human studies have found that urban upbringing and residing in areas with higher degrees of urbanization are both associated with elevated risks of anxiety, depression and schizophrenia (Krabbendam and Van Os, 2005). The underlying mechanisms of social stress and isolation have been shown to progress via neurological pathways (Eisenberger et al., 2003). Specifically, functional MRI studies have corroborated the neural etiology of urban upbringing and habitation on social stress, processing via enhanced activities in perigenual anterior cingulate cortex (pACC) and amygdala (Lederbogen et al., 2011). At another scale, a cross-temporal meta-analysis of Chinese studies identified degree of urbanization as a predictor of loneliness among adults, primarily attributed to reductions in social connectivity attributed to first-hand rural-urban migration experience (Yan et al., 2014).

Notwithstanding the expansion in understanding of human mental health and urban living, there has thus far been no systematic study directly linking objective measures of residential unit density with loneliness and social isolation for a large cohort. To address this gap, we employ data from a national-level UK population cohort with a modelled and linked geospatial database of urban environmental exposures. We fit models that examine independent dose-response relationships between objectively measured residential density within pre-specified functional neighbourhoods, and loneliness and social isolation, adjusting for other built environment and personal attributes. We hypothesize that in spite of the opportunities for positive social interactions facilitated by urbanization, higher housing densities are associated with more isolation and loneliness. Following an urban sociology tradition already cited (Berkman et al., 2000), we assume that this is primarily attributed to unwanted social interaction (negative exposure), paucity of meaningful social interaction (lack of positive exposure), and limited capacity to process social stress and anomie (neuro-response to such exposures) (Durkheim, 1897). We develop dose-response relationships between residential density and loneliness and social isolation, as well as testing for effect modification by key individual variables. We offer this as the largest scale and most detailed test of Durkheim's notion of urban anomie ever conducted.

2. Materials and methods

2.1 Study sample

Our cross-sectional observational study employed the full baseline data from the UK Biobank to examine associations between neighbourhood residential density and loneliness and social isolation. The UK Biobank is an extensively phenotyped population cohort of 502,488 adult participants aged 37–73 at recruitment over 2006-2010 and residing within a 25-mile radius of one of 22 collection centres (which are also major cities) (Sudlow et al., 2015). Approximately, 9.2 million prospective participants enlisted in the National Health Service patient register were originally invited to participate in the study, eventually achieving a response rate of 5.5%. The baseline data comprised a variety of phenotypic information (including socio-demographics, lifestyle, and medical history), genetic information, imaging and bio-samples of participants' blood, urine and saliva. The cohort participants are mostly urban residents, with 86.2% residing in areas classified as 'urban', and have a relatively high residential stability, with 87.6% of participants having resided in their current address for >3 years and 80.5% for >5 years. Upon full recruitment, additional environmental enhancements were conducted, including linked databases of objectively modeled built environment attributes within participants' functional residential catchments as well as individual air pollution exposures (Sarkar et al 2015a). The present study comprises an analytical sample of 405,925 participants (80.8% of the full cohort) with valid data on outcome and key covariates and recruited over the period 4 April 2006–1

October 2010 and recruited from one of the 21 UK Biobank collection centres (see Figure S1 for the spatial catchment areas for participant recruitment).

The UK Biobank is an open-access resource for beneficial public health research, receiving generic ethical approval from the National Health Service National Research Ethics Service (Ref: 11/NW/0382) and all study participants gave informed electronic consent during baseline. The detailed study protocol is available elsewhere (UK Biobank, 2007). We submitted a research proposal and data access application that was approved by the UK Biobank Scientific Committee (approved application no. 11730). We are also the creators of the objective built environment exposure measures in the UK Biobank database.

2.2 Outcome measures

Loneliness and social isolation were measured with previously validated scales in the UK Biobank cohort and other studies (Elovainio et al., 2017; Hakulinen et al., 2018; Hughes et al., 2004). Both were coded as two-factor outcomes (case coded as 1 versus non-case coded as 0) on the basis of the scales' value distributions. Loneliness was ascertained through two questions, namely: i) "Do you often feel lonely?" (coded as 0=No, 1=yes) ii) "How often are you able to confide in someone close to you?" (0= almost daily/2-4 times a week/about once a week/about once a month, 1= once every few months/never or almost never). Participants scoring 2 were defined as being lonely while those with lower score ranging between 0-1 were not lonely. As in a previous study (Elovainio et al., 2017), a social isolation scale was developed comprising three questions, namely: i) "Including yourself, how many people are living together in your household? Include those who usually live in the house such as students living away from home during term, partners in the armed forces or professions such as pilots" (coded as 0=greater than 1, 1=living alone) ii) "How often do you visit friends or family or have them visit you?" (0=almost daily/2-4 times a week/about once a week/about once a month, 1=once every few months/never or almost never/no friends/family outside household iii) "Which of the following do you attend once a week or more often? You can select more than one" (the list of social activities included participation in sports club or gym, pub or social pub, religious groups, adult education and other group activities and coded as: 0=engaging in one or more of weekly social activities, 1=not participating in any weekly social activities). Participants with a combined scale score of 2-3 were defined as socially isolated, while those with scores ranging between 0-1 were not.

2.3 Measures of residential density and built environment

Residential density and built environment variables were derived from a pre-linked spatial database of health-influencing exposures, the UK Biobank Urban Morphometrics Platform (UKBUMP) (Sarkar et al., 2015a). UKBUMP is an individual-level database (developed by this research team) comprising 750-plus built environment variables of density, destination accessibility, design and morphology, and physical environment, all modelled within multiple street catchments of each UK Biobank participant's residences. UKBUMP development involved geocoding of UK Biobank participant's residential addresses, delineation of multi-scalar residential neighbourhood catchments and morphometric development by running a series of geospatial and network analyses algorithms upon multiple UK-wide datasets including UK-wide AddressBase Premium data of Ordnance Survey GB (OS GB), remotely sensed data, digital terrain topographical models and other datasets, and subsequent linkage to anonymized UK Biobank participant IDs. UKBUMP is therefore a ~750 variable description of the built and natural environment around the homes of ~500,000 cohort subjects.

UKBUMP used the UK-wide AddressBase Premium dataset of OS GB comprising 36 million valid address point features with 550 different land-use classifications to measure land-use densities around the residential catchments of cohort participants' geocoded residences. The overall residential density, in units/km^2, was measured as previously (Sarkar et al., 2017) in terms of the total number of detached, semi-detached, terraced dwellings and self-contained flats (OS GB land use code RD, RD02, RD03, RD04, and RD06) within multi-scalar residential street catchments of a participant's residences and expressed as:

$$RD_i^{m-Km} = \frac{n_1 RD + n_2 RD02 + n_3 RD03 + n_4 RD04 + n_5 RD06}{A} \quad \ldots\ldots\ldots\ldots\ldots(1)$$

where RD_i^{m-Km} is the overall residential density for a cohort participant 'i' within an m-Km street catchment; n_1, n_2, n_3, n_4, and n_5 are the number of housing units within the various housing typologies, namely, residential-unclassified (RD), detached (RD02), semi-detached (RD03), terraced (RD04), and self-contained flats (RD06) and A is area under m-Km residential street network catchment. The value of m was taken as 1- and 2-Km to represent functional neighbourhood space used by the resident for daily activities. For the purpose of sensitivity tests we also created residential density exposures by housing types, classified as detached (RD02), semi-detached (RD03), terraced (RD04), and self-contained flats (RD06) in the AddressBase Premium database and defined as:

$$RD02_i^{m-Km} = \frac{n_2 RD02}{A} \quad \text{..............(2)}$$

$$RD03_i^{m-Km} = \frac{n_3 RD03}{A} \quad \text{..............(3)}$$

$$RD04_i^{m-Km} = \frac{n_4 RD04}{A} \quad \text{..............(4)}$$

$$RD06_i^{m-Km} = \frac{n_5 RD06}{A} \quad \text{..............(5)}$$

Among the other built environment exposure variables used in the current study, public transport data was compiled from AddressBase Premium (CT08) and the National Public Transport Access Node database and density was expressed as the intensity of bus stops and train stations within a participant's residential catchment. Densities were measured at two neighbourhood scales, respectively using residential network catchments of 1.0 and 2.0 Km radii.

Destination accessibility (DA_i) of the home of cohort participant *i* was measured as the mean street network distance (ND) from participant *i*'s dwelling, to eleven key destinations, namely, community hall/facility (CC04), community library (CL03), recreation and leisure (CL07), educational institutions (CE01, CE02, CE03, CE04), retail service agents and post office (CR02), pubs/bars/night clubs (CR06), restaurant/cafeteria (CR07) and places of worship (ZW) (measured by running ArcGIS Network Analyst algorithm upon the OS GB's street network database, Integrated Transport Network (ITN) layer), expressed as:

$$DA_i = \frac{\sum(ND_{CC04} + ND_{CL03} + ND_{CL07} + ND_{CE01} + ND_{CE02} + ND_{CE03} + ND_{CE04} + ND_{CR02} + ND_{CR06} + ND_{CR07} + ND_{ZW})}{11} \quad \text{...............(6)}$$

Street-level movement density was modelled at a range of spatial scales of m-metres ranging from 400 meters to 50 Km, to capture micro-, meso- and macro-level effects of surrounding urban features on psycho-social response, bearing in mind that urban experience rests on different temporal and spatial behavior regimes, such as daily visits to general purpose store, less regular visits to green spaces, leisure facilities, relatives and friends in other neighbourhoods and so on (Hillier and Hanson, 1989). Movement density was modelled with the spatial design network analysis (sDNA) software as described previously (Cooper et al., 2012; Sarkar et al., 2017), from the ITN street network layer comprising 5 million street links covering a 50 km radius around the 21 UK Biobank urban centres. The measure is expressed as betweenness centrality (BC), also sometimes termed as through-movement flow. It is a measure of relative centrality of a street link, being proportional to the simulated count of movements passing through a link from and to all other parts of the network, assuming that journeys in the network follow the shortest angular path connecting any pair of nodes in the network. Each street link was allocated a betweenness value based on through-movement from and to all the other links in a network within the predetermined network radius. Following convention, we standardized BC by weighting it with length of the link to account for the fact that longer links (street segment between two junctions) generally support larger number of trips. In graph terminology, link length-weighted BC of x in a graph **G** comprising N links may be defined as:

$$BC(x)_i^m = \sum_{y \varepsilon N} \sum_{z \varepsilon \boldsymbol{R} y} L(y)L(z)P(z)OD(y,z,x) \ \ldots\ldots\ldots\ldots (7);$$

where y and z are the geodesic end points;
Ry is the set of links within a defined radius from y;
L(y) and L(z) are length of links y and z respectively;
Pz is the proportion of link z within the defined radius and the function OD is defined as:

$$OD = \begin{cases} 1, & if\ x\ is\ on\ the\ geodesics\ from\ y\ to\ z \\ \frac{1}{2}, & if\ x \equiv y \not\equiv z \\ \frac{1}{2}, & if\ x \equiv z \not\equiv y \\ \frac{1}{2}, & if\ x \equiv z \equiv y \\ 0, & otherwise \end{cases}$$

$BC(x)_i^m$ represents the BC values of the street link x nearest to the geocoded residence of cohort participant *i*, at a spatial scale of m-metres. A spatial scale of walkable distance (equivalent to 10-minute walk) was employed in the present study to measure betweenness at a walkable scale.

Among the physical environment metrics influencing active living and salutogenic exposures, terrain variability, considered a metric of friction (resistance) to movement was modelled from a

5 metre resolution BlueSky digital terrain model. The digital terrain model comprised topography data representing the terrain in the form of a grid of spot heights. We modelled terrain variability as the standard deviation (variation) in slope within a 500-metre residential catchment. Residential greenness has been shown to be a salutogenic exposure and was modelled in our study using remotely-sensed colour infrared data and a Normalized Difference Vegetation Index (NDVI), which has been employed as an urban greenness metric in epidemiological research (Rhew et al., 2011). We employed a previously validated 0.5-metre resolution mean-NDVI model, derived from remotely sensed BlueSky color infrared imageries. Mean NDVI was measured within a 500 metre residential buffer of each UK Biobank participant, as validated in previous studies (Sarkar, 2017; Sarkar et al., 2018; Sarkar et al., 2015b).

2.4 Individual-level covariates

Socio-demographic covariates comprised age (coded as a three factor variable: <50, ≥50 and <60, ≥60 years); sex (male versus female); highest qualification (five-factor variable: none; National Vocational Qualification, Higher National Diploma, Higher National Certificate, or other professional qualification; O-levels, General Certificate of Secondary Education, or Certificate of Secondary Education; A-levels or AS levels; college or university degree); employment status (three-factor variable: employed; retired; and unemployed/home maker/others); and average household income before tax (coded as a four-level factor variable: <£18,000, £18,000–30,999, £31,000–51,999, ≥£52,000). Lifestyle factors comprised number of children (coded as zero, one, two and three or more), mobile phone usage per week in the last three months (coded as <5, 5-29, 30-59 and ≥60 minutes) and quartiles of metabolic equivalent (MET) minutes per week of walking. We include these because we hypothesize that children in the family will have protective effects on loneliness and social isolation. Also, the link between mobile phone usage and loneliness has been established; while walking behaviour, as a primary attribute of active living, is hypothesized to be protective on loneliness and social isolation. Risk factors modelled, included smoking status (non-smoker, past smoker and current smoker); body mass index (<25 kg/m^2; ≥25 kg/m^2 and <30 kg/m^2; and ≥30 kg/m^2); and comorbidities of cardio-metabolic risks (none; high blood pressure; or heart attack, angina, or stroke; both high blood pressure and heart attack, angina, or stroke); and doctor-diagnosed nerves, anxiety and depression (none versus prevalent).

2.5 Statistical analysis

A series of binary logistic regression models with robust standard errors were developed to examine the associations of loneliness and social isolation with residential density measured within 1-Km residential catchment. Model covariates were assigned *a priori* on the basis of the literature on potential associations and hypothesized links. Blocks of variables were sequentially adjusted for in our analyses. Model 1 adjusted for socio-demographic variables; model 2 further adjusted for lifestyle and risk factors; model 3 additionally adjusted for built environment exposures; while model 4 was the fully-adjusted model that further adjusts for physical environment variables. At each stage, model fit and collinearity diagnostics were assessed to test for parsimony. We checked the distribution of model variables and those with skewness were transformed into categories to avoid misspecification. As a sensitivity analysis, we reran the models with residential density measured within 2-Km street catchment of residences rather than 1-Km. We further fitted restricted cubic spline (RCS) models with Harrell's knots (Harrell, 2015) to capture the non-linear dose-response associations between residential density and odds of loneliness and social isolation. As a further sensitivity test, we examined association of residential density by type of dwelling (as classified in the AddressBase Premium database as: detached, semi-detached, terraced and self-contained flats) with loneliness and social isolation. In single-housing type models, we examined the associations with the four dwelling types separately; and in a multi-housing type model, we examined the combined effects of density with all four types of dwelling entered simultaneously in the model. We also examined associational effect modification by sex, employment status, and household income. All statistical analyses were conducted using Stata version 16. Finally, to verify the robustness of our effect estimates after accounting for missing data across covariates, we performed multiple imputation by chained equations (MICE) in Stata, creating 20 imputation datasets to impute for missing covariates (Sterne et al., 2009). For cohort participants with data on outcome and exposure (residential density), we employed all variables (outcome, exposure and covariates) to impute for missingness across highest educational qualification, employment status, household income, number of children, MET minutes per week for walking, weekly usage of mobile phone in past 3 months, smoking status, BMI, cardio-metabolic risks, and doctor-diagnosed nerves, anxiety and depression, street-level physical walkability, traffic intensity in the nearest road, terrain variability and residential greenness.

3. Results

After excluding cases for missing variables across key socio-demographics (78,647 excluded, 15.7%) and residential density (14,774 excluded, 2.9%), a total of 390,169 (77.6%) participants were available for analysis in the loneliness model and 404,187 (80.4%) for social isolation. The descriptive characteristics of the sample are presented in Table 1. Overall 24,217 (6.21%) participants were lonely while, 36,408 (9.01%) were socially isolated. The mean age of the sample was 56.18 (SD=8.1) years while 52.6% were female. The mean residential unit density within 1 Km was 1,893.7 (SD=1 124.7) units/km^2 and ranged between 0 and 10,513.2 units/km^2, with an interquartile range of 1,037.1 units/km^2. The distribution of residential density is presented in Appendix Figure S2. The mean variance inflationary factor of the models remained between 2.15 and 2.38 indicating low collinearity. We also performed Wald's test for each model and employed the criterion of p-value<0.005 to check for the significance of covariates entered in to the models.

Logistic models examining associations between residential density of all housing types within 1-Km street catchment and loneliness and social isolation are presented in Table 2. Residential density was associated with higher odds of loneliness (OR: 1.045, 95% CI: 1.03-1.06, p<0.0001) and social isolation (OR: 1.171, 1.16-1.18, p<0.0001) in our minimally-adjusted models, controlling for socio-demographic covariates (model 1). Sequentially adjusting for blocks of variables associated with lifestyle and risk factors (model 2), built environment (model 3) and physical environment (model 4), the model fit was enhanced, with higher log-likelihood, and the effect sizes of residential density attenuated as confounding influences were isolated. The fully-adjusted models (model 4) with continuous outcomes indicate that an increment in residential density of 1,000 units/km^2 within a 1-Km residential catchment was independently associated with 2.8% higher odds of loneliness (OR: 1.028, 1.01-1.05, p=0.0057) as well as 11.4% higher odds of social isolation (OR: 1.114, 1.10-1.13, p<0.0001). The results remained consistent in our models when employing quartiles of residential density. In our minimally-adjusted models controlling for participants' socio-demographic characteristics (model 1), in reference to the lowest density quartile, participants in the higher quartiles had higher odds of loneliness OR_{Q3}: 1.096, 1.05-1.14, p<0.0001 and OR_{Q4}: 1.164, 1.12-1.21, p<0.0001 for the third and fourth quartiles respectively) and social isolation (OR_{Q2}: 1.053, 1.02-1.09, p=0.0032; OR_{Q3}: 1.136, 1.10-1.17, p<0.0001 and OR_{Q4}: 1.492, 1.44-1.54, p<0.0001 for the second, third and fourth quartiles respectively). Consistent with our continuous models, the model fit was enhanced, while the effect sizes were attenuated after accounting for the confounders in our fully-adjusted models (model 4). In reference to participants residing in the lowest density quartile, those in the third and the fourth quartiles had higher odds of loneliness (OR_{Q3}: 1.076, 1.01-1.15, p=0.0241 and OR_{Q4}: 1.144, 1.07-1.22, p=0.0001 for the third and fourth quartiles respectively). Similarly, for our social isolation models, participants residing in the higher density quartiles showed higher odds of social isolation in reference to the lowest (OR_{Q3}: 1.083, 1.02-1.15, p=0.0066 and OR_{Q4}: 1.304, 1.23-1.38, p<0.0001 for the third and fourth quartiles respectively). The full description of fully-adjusted models (model 4) is presented in Appendix Table S1.

As a sensitivity analysis, we repeated the analysis using an expanded functional neighbourhood of 2-Km (Table 3). The results remained consistent with our previous analyses using 1-Km catchments, although the effect sizes were more pronounced. In the fully-adjusted 2-Km analyses (model 4), every 1,000 units/km^2 increment in density was associated with 3.5% higher odds of loneliness (OR=1.035, 1.01-1.06, p=0.0034) and 14.3% higher odds of social isolation (OR=1.143, 1.12-1.16, p<0.0001). Consistent results were also obtained using quartiles of residential density (model 4). In reference to the lowest density quartile, those in the higher quartiles had higher odds of loneliness (OR_{Q2}: 1.069, 1.00-1.14, p=0.0490; OR_{Q3}: 1.107, 1.03-1.19, p<0.0061 and OR_{Q4}: 1.183, 1.10-1.28, p<0.0001 for the second, third and fourth quartiles respectively) and social isolation (OR_{Q2}: 1.098, 1.03-1.17, p=0.0022; OR_{Q3}: 1.110, 1.04-1.19, p=0.0018 and OR_{Q4}: 1.418, 1.32-1.52, p<0.0001 for the second, third and fourth quartiles respectively). A more pronounced effect size for density with a 2-Km catchment may suggest a scale-effect in the relationship between urban density and psycho-social malaise. Full models are presented in Appendix Table S2.

To test for bias attributable to missing data across covariates, the re-analyses using imputed data produced consistent results (in terms of size of effect estimates and their significance) as our primary analyses for both loneliness and social isolation. Results of imputation models examining association between residential density at 1- and 2-Km and loneliness and social isolation are presented in Appendix Table S3.

We conducted additional sub-group analyses to examine associations between 1-Km residential density, loneliness and social isolation, by sex, employment status and household income (illustrated in Figure ~~2~~1). We observed a more pronounced detrimental effect of residential density for males than for females, with the interaction being significant only for loneliness (p<0.0001). Similarly, participants in employment and those retired (p-interaction=0.0177 for loneliness and p=0.0003 for social isolation) and among the middle income (those earning £18,000-30,999 and £31,000-51,999, p=0.0213 for social isolation) showed a more pronounced negative effect.

As a further sensitivity analysis, non-linear RCS models with Harrel's knots were fitted to examine associations of residential density measured at 1- and 2-Km with loneliness and social isolation. We iterated by placing 3-, 4-, and 5-knots at equal percentiles of housing density exposures and eventually 3-knot models were selected based on goodness-of-fit assessed by Akaike information criteria (AIC). Figure ~~1~~2 shows a consistent positive association between loneliness and residential density measured at 1-Km (p-value for linearity = 0.0106 and AIC=85,777.7) as well as 2-Km (p-value for linearity=0.0001, AIC=85,768.7). We also observe similar positive associations between social isolation and residential density measured at 1-Km (p-value for linearity=0.5900, AIC=105,051.5) and 2-Km (p-value for linearity=0.0492, AIC=105,031.4).

Our analyses of the associations of residential density within 1-Km by housing types with loneliness and social isolation are presented in Table 4. In our single-housing type models (Model 1) examining effects of the density of each housing-type, higher density of self-contained flats was associated with higher odds of loneliness (OR_{Q4}: 1.112, 1.04-1.18, p=0.0009 for the highest density quartile in reference to the lowest). But higher density of detached housing was associated with lower odds of social isolation (OR_{Q4}: 0.932, 1.44-1.54, p=0.0045 for the highest density quartile in reference to the lowest), while higher density of terraced housing was associated with higher social isolation (OR_{Q3}: 1.114, 1.06-1.17, p<0.0001 and OR_{Q4}: 1.116, 1.06-1.17, p<0.0001 for the third and fourth density quartiles in reference to the lowest), and so was the density of self-contained flats (OR_{Q3}: 1.099, 1.04-1.16, p=0.0006 and OR_{Q4}: 1.325, 1.25-1.40, p<0.0001 for the third and fourth density quartiles in reference to the lowest). In our multi-housing type models simultaneously examining the associations of densities of detached, semi-detached, terraced and flats (model 2), we found that in reference to the lowest density quartile of detached housing, those in the higher had lower odds of loneliness (OR_{Q2}: 0.931, 0.88-0.99, p=0.0186; OR_{Q3}: 0.921, 0.86-0.99, p=0.0264 and OR_{Q4}: 0.868, 0.79-0.95, p=0.0029 for the second, third and fourth density quartiles in reference to the lowest) and social isolation (OR_{Q3}: 0.872, 0.82-0.93, p<0.0001 and OR_{Q4}: 0.798, 0.73-0.87, p<0.0001 for the third and fourth density quartiles). The density of terraced housing within 1-Km was found to be positively associated with social isolation (OR_{Q3}: 1.168, 1.09-1.25, p<0.0001 and OR_{Q4}: 1.272, 1.17-1.38, p<0.0001 for the third and fourth density quartiles in reference to the first). Similarly, the density of flats was consistently associated with higher odds of loneliness (OR_{Q4}: 1.096, 1.02-1.18, p=0.0105 for the fourth quartile in reference to the first) and social isolation (OR_{Q3}: 1.102, 1.04-1.17, p=0.0012 and OR_{Q4}: 1.289, 1.21-1.37, p<0.0001 for the third and fourth density quartiles in reference to the lowest).

Among the other activity-related and environment exposures, MET minutes per week of walking was consistently associated with lower loneliness (ORs: 0.889, 0.843 and 0.884 for the second, third and highest MET quartiles in reference to the lowest and p<0.0001) and social isolation (ORs: 0.847, 0.863 and 0.857 for the second, third and highest MET quartiles in reference to the lowest and p<0.0001). Street-level activity potential, expressed as the degree of urban road grid connectivity of the street link on which the home address is located, and measured using a network betweenness centrality index was associated with lower social isolation (ORs: 0.907, 0.886 and 0.903 for the second, third and highest betweenness quartiles in reference to the lowest and p<0.0001), exemplifying the importance of urban design in social cohesion. Neighbourhood greenness assessed in terms of NDVI was also beneficial, with each interquartile increment being associated with 2.6% lower odds of social isolation (OR: 0.974, p=0.0357).

4. Discussion and conclusion

In a very large UK-wide population cohort, we report that residential density within a 1-Km street catchment was independently associated with both loneliness and social isolation after adjustments for related socio-demographics, lifestyle and risk factors, and other built and physical environmental exposures. The results remained consistent after a sensitivity test that increased the area of the neighbourhood within which density was measured, from a 1-km to 2-Km network buffer around cohort members' homes. Our study found that each residential density increment of 1,000 units/Km^2 was associated with 2.8% and 11.4% higher odds of loneliness and social isolation respectively. The observed effect sizes in the case of loneliness are relatively small, nonetheless, given that the density of housing is a universal indicator of health-specific built environment, the enduring value of optimizing residential density as a population-based preventive strategy for reducing loneliness and social isolation should not be underestimated (Rose, 1992). This is, to our knowledge, the first study at this scale and robustness and employing highly characterized phenotypic data from a national-level health cohort with detailed individual-level built environment exposures, to examine the trajectory of loneliness and social isolation across a full national gradient of housing density. The policy importance of this topic has been recently exemplified by the Loneliness strategy of the UK Government (HM Government, 2018) as well as in the USA (Holt-Lunstad, 2018). Our study suggests the need for greater synergy between national-level loneliness strategies and urban planning policy such as suburban densification policies.

This is also the first large-scale study to examine mental health impacts of residential unit density by housing-types (units being categorized as detached, semi-detached, terraced and self-contained flats). Higher density of detached housing was found to be beneficial, with the highest density quartile being associated with 13.2% and 20.2% lower odds of loneliness and social isolation respectively in reference to the lowest quartile. Contrarily higher density of flats was found to be positively associated with both outcomes, with highest density quartile being associated with 9.6% and 28.9% higher odds of loneliness and social isolation respectively in reference to the lowest. Our results are consistent with the few previous findings that have reported adverse psychological effects of objectively measured multi-dwelling housing and high-rise apartments (Evans et al., 2003; Panczak et al., 2013). This has important urban planning as well as social policy and housing policy implications, since not only is the planning density of housing units (packing) significant for mental health and wellbeing, but so also is the configuration and the mixture of housing types in neighbourhoods. The policy and design dimensions need careful consideration with the objective of optimizing compact living for ameliorating social stress from a population health perspective, and reducing the burden of loneliness, social isolation and associated chronic disease in cities.

A few previous studies have reported mostly broad urban-rural variations in loneliness and social isolation, and using ecological study designs. A recent large Canadian cohort study (N = 48,330) reported 20% and 2% higher odds of social isolation and loneliness in the urban core versus rural areas, although the results remained insignificant (Menec et al., 2019). A smaller study of n=124 older adults aged 55-92 years in Minneapolis metropolitan area, USA, categorized the study area into high and low density neighbourhoods reporting 1.45 and 2.89 times higher odds of loneliness and social isolation respectively in the former (Finlay and Kobayashi, 2018). Similar associational trends have been reported between population density and mental health outcomes (Walters et al., 2004). A recent meta analyses of 25 studies of older adults (≥60 years) reported a significant correlation between loneliness and a broad measure of urbanization level (correlation coefficient $r=0.69$, $P<0.01$) (Yan et al., 2014).

Our study found significant interaction between residential density and sex in the case of loneliness, with larger effect sizes across higher density quartiles in males. This might be attributed to the sexual differences in processing social stress and is consistent with previous findings that females may be more tolerant to social stress given their oxytocin-induced affiliative ‘tend-befriend’ stress responses, as opposed to testosterone/vasopressin-facilitated ‘flight-fight’ responses to stress in males (Rose and Rudolph, 2006; Taylor et al., 2000). As a result, men are also less likely to disclose emotional distress, making them more vulnerable to loneliness (Holwerda et al., 2012). Previously Japanese men residing in non-rural areas were found more likely to be lonely than women (van den Broek, 2017). The detrimental effects of higher density were relatively pronounced among the retired, in models of both loneliness and social isolation. With a mean age of 63.84 (SD=3.8 years) in the retired category and lower functional ability, retired participants are likely to spend more time in relatively small functional neighbourhoods, and thus are more exposed to immediate residential density relative to other population sub-groups.

The exact psycho-social pathways from high density to loneliness and social isolation are yet to be deciphered. It has been suggested that housing density yields both physical and social effects; higher unit density is a proxy of lower per-capita space and crowding, leading to unwanted contacts, lack of privacy and social overload. The resulting increase in the frequency of unanticipated superficial encounters may lead to loss of control over the environment, producing stress (Evans et al., 2001; Rodin, 1976). Coping strategies, in most instances, manifest themselves in the form of withdrawal to avoid averse social outcomes (as with Calhoun’s rodent experiments), learned helplessness and purposive avoidance, in some instances resulting in confinement to only a very limited circle of immediate relationships (Baum et al., 1978; Baum and Valins, 1979). Unwanted social interactions have also been evidenced to cause loss of support networks which further enhances risks of loneliness and social isolation (Evans et al., 1989). On the other hand, low residential unit density corresponds to suburbs and exurbs, characterized by lower levels of stress attributed to more defensible personal space, lower odds of unwanted interactions, and possibly a higher social capital (Halpern, 2014). Our models control for differences in greenness between suburbs and more central environments and suggest that higher housing density and less greenness may have independent effects in increasing loneliness and social isolation. We found that the urban design metrics of betweenness centrality and green exposure, as well as overall and type-specific housing unit density, were also independently significant for social isolation models. This may imply that there can be multiple ways of attempting to reduce loneliness and increase social interaction including by landscape and urban design besides optimizing density and adjusting the housing mix.

We found that an analysis using a 2-Km buffer to measure exposure to density, showed stronger association with loneliness and with social isolation than with a 1Km buffer. This is the first robust evidence suggesting that scale of density matters. For a given residential density, larger clusters (spatially bigger concentrations of people) are associated with higher risks of loneliness and social isolation than smaller clusters. This implies that both density and spatial extent of density are affective on loneliness and social isolation. Scale effects have been observed in other negative urban externalities such as crime and congestion (Bettencourt et al., 2010). Future studies should look into the scaling effects of health parameters with respect to the size of planned homogeneous urban neighborhoods and entire cities.

Biologically, it has been suggested that urban social stress has the potential to modulate physiological processes by altering the neuroendocrine and autonomic nervous system activities (Norman et al., 2012). It has also been shown to reduce diurnal variations in hypothalamic-pituitary-adrenal (HPA) axis functioning (McEwen, 2005) and larger cortisol awakening responses and elevated cortisol output (Grant et al., 2009). Previously, human brain fMRI studies have also established direct correlation between degree of urbanicity and amygdala and pACC activity (Lederbogen et al., 2011). A series of animal experiments provide some evidence on the neurobiological pathways (Lee et al., 2018; Wood et al., 2010), although exact mechanisms in humans remain to be ascertained.

We found that the association between density and social isolation is much stronger than between density and loneliness. Loneliness and social isolation have different connotations. Our index of loneliness acts as a proxy for a psychological experience, 'feeling lonely', a marker of perceived dissatisfaction with the frequency and closeness of social contacts. Social isolation denotes an objective and measurable absence of social contacts and hence the later likely produces higher effects (Finlay and Kobayashi, 2018; Steptoe et al., 2013). If this is the case, the conversion of social isolation to loneliness will be moderated by multiple factors such as coping ability of individuals, age and gender. Future biological and socio-environmental studies should aim to better understand the relationship between social-isolation and loneliness and their relationship with stress, social pathology and mental health in urban settings.

Strengths of the study include the use of the highly characterized UK-wide Biobank dataset of unprecedented size and quality, objective and detailed measures of individual-level built environment exposures derived from the UKBUMP dataset, including assessment of residential unit density at multiple spatial scales, and adjustments for a range of built environment attributes and individual social and health covariates. We were also able to examine dose-response relationship between residential density and loneliness and social isolation, as well as sub-group effects. We sensitivity-tested the scale of the geographical neighbourhood used to test density effects and found our results to be robust. The study has several limitations. Cross sectional design limits causal inference and also means that neighbourhood self-selection and selective migration cannot be ruled out. Nonetheless, the overall cohort population was relatively stable and the mean length of time in a residential address for the study sample was 16.94 years (SD=12.2 years). Secondly, as in any observational study, residual confounding cannot be completely ruled out, even though we adjusted for a range of exposures and personal covariates. As subsequent waves of UK Biobank health data get accumulated over time, we plan to conduct longitudinal analyses adjusting for time-varying built environment, covariates and duration of follow-up period to complement our present study. Thirdly, most of the UKBUMP metrics of urban exposures were assessed at the end of the baseline in 2010, while the participants were recruited over 2006-2010. Nonetheless, we maintain that the temporal mismatch will not have significantly influenced our effect estimates given that urbanization in the UK is at saturation level and changes in density and other built environment attributed over time will have been minimal. Lastly, UK Biobank is an adult cohort with a relatively low response rate. The comparison of socio-demographics and health-related characteristics with the general population of UK can be found elsewhere (Fry et al., 2017). It may be likely that the prevalence of loneliness and social isolation may not be representative of the whole UK and findings may not be strictly generalizable to the whole UK population. Our study follows the accepted epidemiological justification of large non-representative cohorts on grounds that the cohort population contains sufficient variability in the systematically measured exposures (residential densities and other built environment qualities measured at individual level) and outcome variables (loneliness and social isolation) to form a valid and reliable experiment across meaningful value gradients. We note, importantly, that the residential density gradient assessed in our models, corresponds to the density range for the UK reported in other studies and official statistics. At the same time, when taken in a global context UK lies in the middle part of the residential density spectrum with countries like Australia and US lying at the lower end, while Hong Kong, China and India occupy the higher end. Future studies should examine the effects of residential density in multi-country settings with diverse socio-cultural and lifestyle level factors.

The urban centres of the world, besides being synonymous with economic growth and development, also sustain hectic lifestyles often associated, anecdotally, in scientific studies and in psycho-social theory, with higher degrees of social stress. The reason why people walk at higher speeds in larger cities is not just due to the value of time being higher through longer commutes and higher wages (Gordon et al., 1989). Loneliness and social isolation are important precursors, falling in the etiologic pathways of most chronic diseases, and there has thus far been scant research evidence on their built environment determinants. This has come a long way since Emile Durkheim's urban anomie. Being an urban- and labor-sociologist, his focus was on social processes as an explanation for the stresses and strains of urban living that result in suicide. 120 years later we have been able to objectively measure the rate at which loneliness and social isolation rise with residential density, controlling for the social and health characteristics of individuals and other built environmental characteristics of their immediate home environments. Durkheim's theory was posed in opposition to the methodological individualism of economics. Twenty-first century urban research brings a second kind of methodological individualism to bear: a recombination of urban planning research and public health and epidemiology. We have measured for the entire UK what economists would call the elasticity of loneliness with respect to density (or the density elasticity of loneliness). In recognition of Durkheim we propose to call this the Anomie Density Ratio (ADR), notwithstanding the philosophical issue about measuring an outcome rather than the alleged structural cause. Actually, we take the approach of Friedrich von Hayek in the sociology-economics debate on Anomie, and point to individual causes, as we have above: enzymatic and other phenotypical and genotypical causes in the individual who is exposed to various social, built and natural environmental exposures. That is not to say that the strains of normlessness in the city do not have an impact on behaviour, and as the new science of epigenetics now allows, an impact on gene expression. The city may yield its psycho-social malaises by both nurture and nature.

From a global perspective, there is an impending need for greater focus on loneliness and social isolation, just as there is for happiness. Systematic data collection and robust analyses from large-number studies, backed by close-up case study research and design and policy experiments, should be able to yield health-sensitive urban public health and planning strategies that mitigate and moderate this most insidious urban diseconomy of scale. The ADR needs calculating for other countries and validating with other methods. It should become an important urban planning and public health policy design parameter. Urban densification in low-middle income economies, and densifying urban regeneration and suburban densification in high income countries will continue apace. So, the crucial question in the present context is: Can this process be better guided by scientific studies of density-health relationships? In his paper, Mitchell (1971) had cited ‘a current consensus in European countries’ that 170 square-feet is the minimum livable space inside a home thought to protect mental health. The COVID-19 pandemic has once again drawn society’s attention to the fundamental question of minimum density, not so much humane density but safe density to sustain public health. Epidemiologic transitions in developed economy have meant chronic diseases kill and impair far more on a regular basis in modern cities than do infectious diseases. We show that residential density, for all its positives, is systematically associated with loneliness and social isolation - precursors to mental and physical health problems and intrinsically unpleasant.

Even though the lost social mores leading to Durkheim's urban anomie are no doubt different to any contributing to loneliness today, still 24,217 of our study sample (6.21%) were lonely and 36,408 (9.01%) were socially isolated. The conditions, we show, worsen with housing density by a factor of 2.8% and 11.4% higher odds of loneliness and social isolation respectively, per additional 1,000 units/Km^2. Further, we found that flatted and terraced neighbourhoods in Britain, are habitats of increasing loneliness as their density increases (controlling for important covariates), while detached homes work the other way. A detached home confers many benefits on its occupant, more than those conferred by a terrace home if we take price as a measure of revealed preference. However, the residential solution seems, reasonably, to be better optimized (for loneliness and isolation) by calibrating adequate mix as well as designing detached homes at higher density. The fact that the ADR pattern can be traced systematically into housing sub-markets is important. It may suggest that what we have observed is not so much anomie (the absence of something – the loss of comforting social mores), as the hard-wiring of degrees of discomfort into the city. Optimizing housing densities and mix in conjunction with designing multi-functional neighbourhood spaces can plausibly reinvigorate positive social interactions improving mental capital of our cities.

Competing interests

The authors declare no competing interests.

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Tables:

Table 1. Characteristics of UK Biobank analytic sample (N=405,925).

Participant characteristics	
Covariates:	
Age in years[a] (Mean, SD)	56.18 (8.1)
Gender N (%):	
Female	213,452 (52.6)
Male	192,473 (47.4)
Highest educational qualification N (%):	
None	60,801 (15.0)
NVQ/HND/HNC/Other professional	47,820 (11.8)
O levels/GCSEs/CSEs	109,289 (26.9)
A levels/AS levels	47,211 (11.6)
College or University degree	140,804 (34.7)
Employment status N (%):	
Employed	247,164 (60.9)
Retired	127,945 (31.5)
Unemployed, home maker, others	30,816 (7.6)
Household income:	
<£18,000	91,297 (22.5)
£18,000 – £30,999	103,550 (25.5)
£31,000 – £51,999	106,552 (26.3)
≥£52,000	104,526 (25.8)
Smoking status N (%):	
Non-smoker	220,932 (54.4)
Previous smoker	141,600 (34.9)
Current smoker	42,347 (10.4)
Missing	1,046 (0.3)
Number of children N (%):	
None	79,317 (19.5)
1	53,260 (13.1)
2	175,235 (43.2)
≥3	96,764 (23.8)
Missing	1,349 (0.3)
Metabolic Equivalent Task (MET) minutes per week for walking:	
Low (Q1)	87,605 (21.6)
Q2	110,302 (27.2)
Q3	77,823 (19.2)
High (Q4)	64,423 (15.9)
Missing	65,772 (16.2)
Weekly usage of mobile phone in last 3 months:	
<5 minutes	70,964 (17.5)
5-29 minutes	133,958 (33.0)
30-59 minutes	59,574 (14.7)

≥1 hour	79,752 (19.7)
Missing	61,677 (15.2)
Body mass index status N (%):	
Normal weight	133,652 (32.9)
Overweight	172,852 (42.6)
Obese	97,535 (24.0)
Missing	1,886 (0.5)
Vascular problems N (%):	
None	287,202 (70.8)
High blood pressure	95,655 (23.6)
Heart attack/ angina/ stroke	10,484 (2.6)
High blood pressure and Heart attack/ angina/ stroke	12,022 (3.0)
Missing	562 (0.1)
Nerves, anxiety and depression N (%):	
None	266,382 (65.6)
Yes	137,397 (33.9)
Missing	2,146 (0.5)
Built environment variables (Mean, SD):	
Residential unit density within 1Km (units/Km^2)[b]	1,893.72 (1,124.7)
Residential unit density within 2Km (units/Km^2)[c]	1,679.96 (1,027.8)
Public transport density within 1Km (units/Km^2)	
Quartile 1 (0-15.7)	102,334 (25.2)
Quartile 2 (15.7-21.9)	101,735 (25.1)
Quartile 3 (21.9-28.6)	101,114 (24.9)
Quartile 4 (28.6-207.2)	100,742 (24.8)
Mean street distance to destinations (m)	
Quartile 1 (0-856.5)	88,141 (21.7)
Quartile 2 (856.5-1175.2)	106,215 (26.2)
Quartile 3 (1,175.2-1,529.6)	105,558 (26.0)
Quartile 4 (1,529.6-4,265.4)	106,011 (26.1)
Street-level movement density	
Quartile 1 (5,076.2-8.53*10E5)	101,727 (25.1)
Quartile 2 (8.53*10E5-2.64*10E6)	101,165 (24.9)
Quartile 3 (2.64*10E6-6.42*10E6)	101,447 (25.0)
Quartile 4 (6.42*10E6-8.75*10E7)	101,135 (24.9)
Missing	451 (0.1)
Traffic intensity in the nearest road	
≤500	380,177 (93.7)
>500	24,242 (6.0)
Missing	1,506 (0.4)
Terrain variability within 500 m (SD, degrees)	
Quartile 1 (0-1.7)	97,006 (23.9)
Quartile 2 (1.7-2.6)	97,745 (24.1)
Quartile 3 (2.6-3.7)	98,008 (24.1)
Quartile 4 (3.7-15.7)	98,635 (24.3)

Missing	14,531 (3.6)
Residential greenness (NDVI) within 500m[b]	0.16 (0.2)
Missing	106,464 (26.2)
Outcome variables	
Loneliness N (%):	
Yes	24,217 (6.0)
No	365,952 (90.2)
Missing	15,756 (3.9)
Social isolation N (%):	
Yes	36,408 (9.0)
No	367,779 (90.6)
Missing	1,738 (0.4)

[a]Range=38-73; Median=57; 25th percentile=50; 75th percentile=63.
[b]Range=0-10,513.2; Median=1,768.3; 25th percentile=1,246.8; 75th percentile=2,283.8.
[c]Range=1.4-8,389.8; Median=1,572.0; 25th percentile=1,070.4; 75th percentile=2,065.9.
[d]Range=-0.6-0.7; Median=0.2; 25th percentile=0.0; 75th percentile=0.3.

Table 2. Association between residential density within 1-Km street catchment and loneliness and social isolation among participants of UK Biobank with valid individual-level and built environment data.

Housing unit density (units/Km² in 1,000 metre residential catchment)	**N (%)**[e]	**Loneliness** OR (95% CI) p-value	**N (%)**[e]	**Social isolation** OR (95% CI) p-value
Model 1[a]	390 169 (6.21)		404 187 (9.01)	
Residential density (increment per 1,000 units/Km²)		1.045 (1.03-1.06) <0.0001		1.171 (1.16-1.18) <0.0001
Log likelihood		-87,727.4		-114,950.9
Residential density (units/Km²) categories:				
Low (Q_1): <1,252.0 – Ref				
Q2: 1,252.0-1,774.6		1.039 (1.00-1.08) 0.0565		1.053 (1.02-1.09) 0.0032
Q3: 1,774.6-2,289.9		1.096 (1.05-1.14) <0.0001		1.136 (1.10-1.17) <0.0001
High (Q_4): >2,289.9		1.164 (1.12-1.21) <0.0001		1.492 (1.44-1.54) <0.0001
Log likelihood		-87,718.6		-115,109.2
Model 2[b]	278 540 (5.79)		285 844 (7.88)	
Residential density (increment per 1,000 units/Km²)		1.030 (1.02-1.04) 0.0001		1.098 (1.09-1.11) <0.0001
Log likelihood		-58,118.8		-71,820.4
Residential density (units/Km²) categories:				
Low (Q_1): <1,252.0 – Ref				
Q2: 1,252.0-1,774.6		1.032 (0.98-1.08) 0.1955		1.035 (0.99-1.08) 0.1173
Q3: 1,774.6-2,289.9		1.059 (1.01-1.11) 0.0191		1.063 (1.02-1.11) 0.0049
High (Q_4): >2,289.9		1.126 (1.07-1.18) <0.0001		1.275 (1.22-1.33) <0.0001
Log likelihood		-58,113.2		-71,855.4

Model 3[c]	277 150 (5.78)		284 417 (7.85)	
Residential density (increment per 1,000 units/Km^2)		1.036 (1.02-1.05) 0.0001		1.102 (1.09-1.12) <0.0001
Log likelihood		-57,776.4		-71,235.9
Residential density (units/Km^2) categories:				
Low (Q_1): <1,252.0 – Ref				
Q2: 1,252.0-1,774.6		1.049 (1.00-1.10) 0.0709		1.057 (1.01-1.11) 0.0193
Q3: 1,774.6-2,289.9		1.085 (1.03-1.15) 0.0033		1.092 (1.04-1.15) 0.0004
High (Q_4): >2,289.9		1.162 (1.10-1.23) <0.0001		1.284 (1.22-1.35) <0.0001
Log likelihood		-57,769.6		-71,265.5
Model 4[d]	204 188 (5.84)		209 519 (7.85)	
Residential density (increment per 1,000 units/Km^2)		1.028 (1.01-1.05) 0.0057		1.114 (1.10-1.13) <0.0001
Log likelihood		-42,829.2		-52,462.9
Residential density (units/Km^2) categories:				
Low (Q_1): <1,252.0 – Ref				
Q2: 1,252.0-1,774.6		1.038 (0.98-1.10) 0.2306		1.046 (0.99-1.11) 0.1097
Q3: 1,774.6-2,289.9		1.076 (1.01-1.15) 0.0241		1.083 (1.02-1.15) 0.0066
High (Q_4): >2,289.9		1.144 (1.07-1.22) 0.0001		1.304 (1.23-1.38) <0.0001
Log likelihood		-42,824.0		-52,496.1

[a] Model 1 adjusted for individual-level socio-demographic covariates (age, sex, highest educational qualification, employment status, household income).

[b] Model 2 adjusted for individual-level socio-demographic covariates plus life style and risk factors (number of children, MET minutes per week for walking, weekly usage of mobile phone in past 3 months, smoking status, BMI, cardio-metabolic risks, and doctor-diagnosed nerves, anxiety and depression)
[C] Model 3 adjusted for individual-level socio-demographic covariates, lifestyle and risk factors plus built environment exposures (street-level physical walkability, density of public transport, traffic intensity in the nearest road, and mean street distance to destinations).
[d] Model 4 is the fully adjusted model adjusting for individual-level socio-demographic covariates, lifestyle and risk factors, built environment exposures plus physical environment (terrain variability and residential greenness).
[e] Number of participants in the model and % of the participants lonely or socially isolated.

Table 3. Sensitivity analysis showing association between residential density within 2-Km street catchment and loneliness and social isolation among participants of UK Biobank with valid individual-level and built environment data.

Housing unit density (units/Km² in 2,000 metre residential catchment)	**N (%)**[e]	**Loneliness** OR (95% CI) p-value	**N (%)**[e]	**Social isolation** OR (95% CI) p-value
Model 1[a]	390 174 (6.21)		404 193 (9.01)	
Residential density (increment per 1,000 units/Km²)		1.044 (1.03-1.06) <0.0001		1.182 (1.17-1.19) <0.0001
Log likelihood		-87,732.7		-114,995.2
Residential density (units/Km²) categories:				
Low (Q_1): <1,077.5 – Ref				
Q2: 1,077.5-1,577.7		1.037 (1.00-1.08) 0.0678		1.038 (1.00-1.07) 0.0294
Q3: 1,577.7-2,070.3		1.072 (1.03-1.11) 0.0004		1.094 (1.06-1.13) <0.0001
High (Q_4): >2,070.3		1.146 (1.10-1.19) <0.0001		1.469 (1.42-1.52) <0.0001
Log likelihood		-87,726.4		-115,117.9
Model 2[b]	278 543 (5.79)		285 847 (7.88)	
Residential density (increment per 1,000 units/Km²)		1.030 (1.01-1.05) 0.0002		1.106 (1.09-1.12) <0.0001
Log likelihood		-58,120.6		-71,828.5
Residential density (units/Km²) categories:				
Low (Q_1): <1,077.5 – Ref				
Q2: 1,077.5-1,577.7		1.036 (0.99-1.09) 0.1413		1.020 (0.98-1.06) 0.3595
Q3: 1,577.7-2,070.3		1.046 (1.00-1.10) 0.0643		1.024 (0.98-1.07) 0.2669
High (Q_4): >2,070.3		1.101 (1.05-1.15) 0.0001		1.263 (1.21-1.31) <0.0001
Log likelihood		-58,118.6		-71,851.8

Model 3[c]	277 153 (5.78)		284 420 (7.85)	
Residential density (increment per 1,000 units/Km^2)		1.039 (1.02-1.06) 0.0002		1.123 (1.10-1.14) <0.0001
Log likelihood		-57,778.1		-71,239.3
Residential density (units/Km^2) categories:				
Low (Q_1): <1,077.5 – Ref				
Q2: 1,077.5-1,577.7		1.066 (1.01-1.13) 0.0238		1.081 (1.03-1.14) 0.0023
Q3: 1,577.7-2,070.3		1.096 (1.03-1.17) 0.0036		1.106 (1.05-1.17) 0.0004
High (Q_4): >2,070.3		1.160 (1.09-1.24) <0.0001		1.339 (1.26-1.42) <0.0001
Log likelihood		-57,774.3		-71,262.4
Model 4[d]	204 191 (5.84)		209 522 (7.85)	
Residential density (increment per 1,000 units/Km^2)		1.035 (1.01-1.06) 0.0034		1.143 (1.12-1.16) <0.0001
Log likelihood		-42,829.1		-52,454.6
Residential density (units/Km^2) categories:				
Low (Q_1): <1,077.5 – Ref				
Q2: 1,077.5-1,577.7		1.069 (1.00-1.14) 0.0490		1.098 (1.03-1.17) 0.0022
Q3: 1,577.7-2,070.3		1.107 (1.03-1.19) 0.0061		1.110 (1.04-1.19) 0.0018
High (Q_4): >2,070.3		1.183 (1.10-1.28) <0.0001		1.418 (1.32-1.52) <0.0001
Log likelihood		-42,823.0		-52,474.7

[a] Model 1 adjusted for individual-level socio-demographic covariates (age, sex, highest educational qualification, employment status, household income).

[b] Model 2 adjusted for individual-level socio-demographic covariates plus life style and risk factors (number of children, MET minutes per week for walking, weekly usage of mobile phone in past 3 months, smoking status, BMI, cardio-metabolic risks, and doctor-diagnosed nerves, anxiety and depression)

[c] Model 3 adjusted for individual-level socio-demographic covariates, lifestyle and risk factors plus built environment exposures (street-level physical walkability, density of public transport, traffic intensity in the nearest road, and mean street distance to destinations).
[d] Model 4 is the fully adjusted model adjusting for individual-level socio-demographic covariates, lifestyle and risk factors, built environment exposures plus physical environment (terrain variability and residential greenness).
[e] Number of participants in the model and % of the participants lonely or socially isolated.

Table 4. Association between residential density within 1 Km street catchment and loneliness and social isolation by housing types within a 1-Km street catchment.

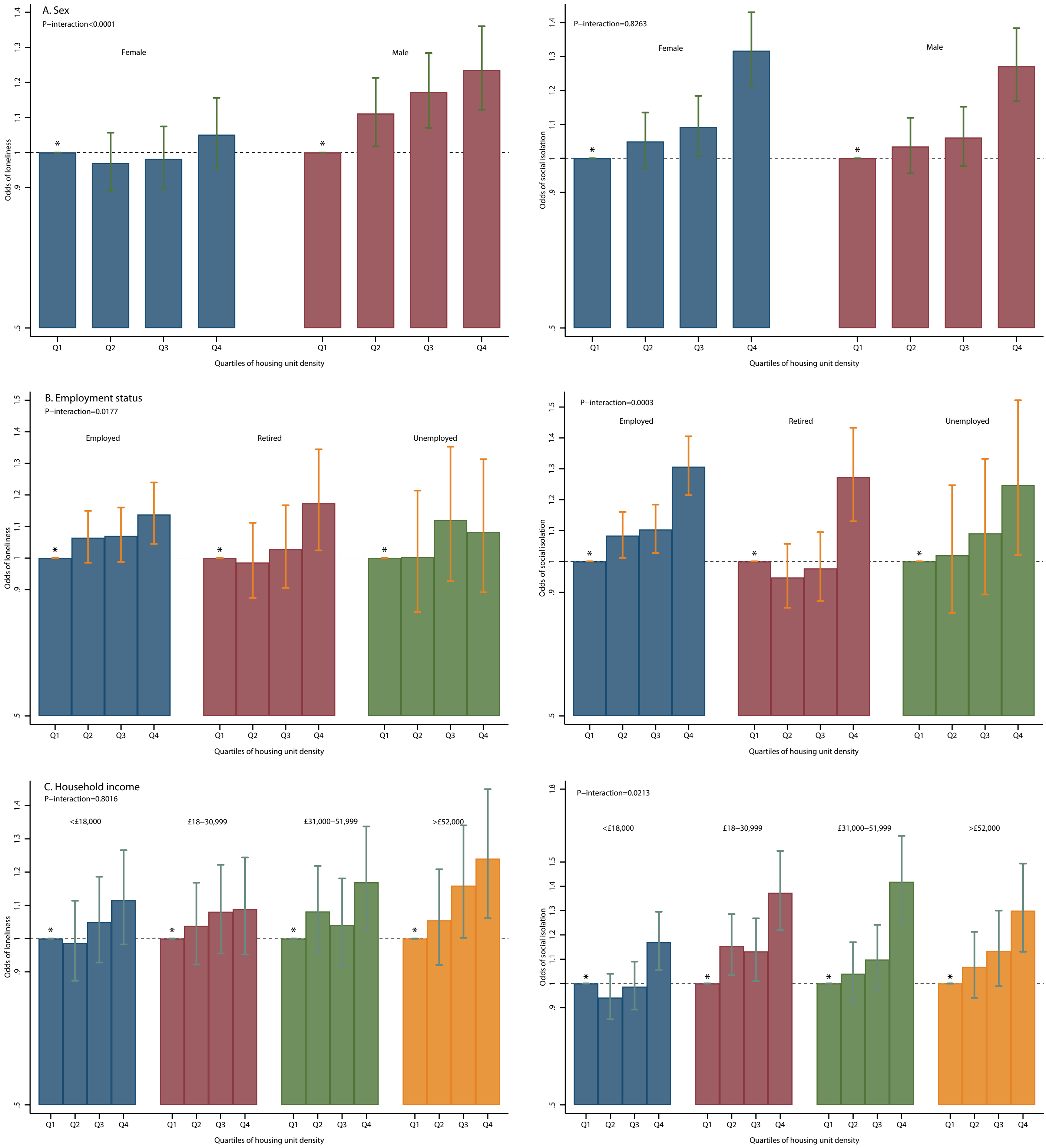
Housing unit density by type*	**Loneliness** (N=204 195) OR (95% CI) p-value		**Social isolation** (209 527) OR (95% CI) p-value	
	Model 1[a]	**Model 2**[b]	**Model 1**[a]	**Model 2**[b]
Detached housing density categories:				
Low (Quartile 1) – Ref				
Quartile 2	0.958 (0.91-1.01) 0.1093	0.931 (0.88-0.99) 0.0186	1.006 (1.02-1.09) 0.7836	0.960 (0.912-1.01) 0.1230
Quartile 3	0.987 (0.94-1.04) 0.6334	0.921 (0.86, 0.99) 0.0264	0.964 (1.10-1.17) 0.1197	0.872 (0.82-0.93) <0.0001
High (Quartile 4)	0.968 (0.92-1.02) 0.2448	0.868 (0.79, 0.95) 0.0029	0.932 (1.44-1.54) 0.0045	0.798 (0.73-0.87) <0.0001
Log likelihood	-42,832.9		-52,551.5	
Semi-detached housing density categories:				
Low (Quartile 1) – Ref				
Quartile 2	0.990 (0.94-1.04) 0.6806	1.010 (0.95-1.08) 0.7603	1.005 (0.96-1.05) 0.8393	0.979 (0.93-1.03) 0.4532
Quartile 3	1.024 (0.97-1.08) 0.3831	1.057 (0.98-1.15) 0.1773	1.027 (0.98-1.07) 0.2719	0.992 (0.92-1.06) 0.8193
High (Quartile 4)	1.023 (0.97-1.08) 0.4040	1.059 (0.95-1.18) 0.2799	0.995 (0.95-1.04) 0.8370	0.920 (084-1.01) 0.0739
Log likelihood	-42,833.2		-52,556.7	
Terraced housing density categories:				
Low (Quartile 1) – Ref				
Quartile 2	0.993 (0.94-1.05) 0.8062	0.992 (0.93-1.05) 0.8043	1.034 (0.98-1.09) 0.1828	1.047 (0.99-1.11) 0.1020
Quartile 3	1.030 (0.97-1.09) 0.2910	1.027 (0.95-1.10) 0.4611	1.114 (1.06-1.17) <0.0001	1.168 (1.09-1.25) <0.0001
High (Quartile 4)	1.040 (0.98-1.10) 0.1682	1.050 (0.96-1.15) 0.3110	1.116 (1.06-1.17) <0.0001	1.272 (1.17-1.38) <0.0001
Log likelihood	-42,832.5		-52,542.9	
Density of self-contained flats categories:				
Low (Quartile 1) – Ref				
Quartile 2	1.044 (0.99-1.10) 0.1368	1.048 (0.99-1.11)0.1231	1.043 (0.99-1.10) 0.1110	1.047 (0.99-1.10) 0.0923

Quartile 3	1.057 (1.00-1.12) 0.0665	1.055 (0.99-1.13) 0.1103	1.099 (1.04-1.16) 0.0006	1.102 (1.04-1.17) 0.0012
High (Quartile 4)	1.112 (1.04-1.18) 0.0009	1.096 (1.02-1.18) 0.0105	1.325 (1.25-1.40) <0.0001	1.289 (1.21-1.37) <0.0001
Log likelihood	-42,828.7	-42,822.5	-52,491.5	-52,453.1

*Adjusted models presented controlling for individual-level socio-demographics (age, sex, highest educational qualification, employment status, household income), lifestyle and risk factors (number of children, MET minutes per week for walking, weekly usage of mobile phone in past 3 months, smoking status, BMI, cardio-metabolic risks, and doctor-diagnosed nerves, anxiety and depression), built environment exposures (street-level physical walkability, density of public transport, traffic intensity in the nearest road, and mean street distance to destinations) and physical environment (terrain variability and residential greenness).

[a]Single-housing type models, wherein density of specific housing type classified as detached, semi-detached, terraced and self-contained flats were entered separately in respective models.

[b]Fully-adjusted multi-housing type model, wherein density of specific housing type classified as detached, semi-detached, terraced and self-contained flats were entered simultaneously in to the model.



A. Sex
P–interaction<0.0001
Female
Male
Odds of loneliness
Quartiles of housing unit density
P–interaction=0.8263
Female
Male
Odds of social isolation
Quartiles of housing unit density
B. Employment status
P–interaction=0.0177
Employed
Retired
Unemployed
Odds of loneliness
Quartiles of housing unit density
P–interaction=0.0003
Employed
Retired
Unemployed
Odds of social isolation
Quartiles of housing unit density
C. Household income
P–interaction=0.8016
<£18,000
£18–30,999
£31,000–51,999
>£52,000
Odds of loneliness
Quartiles of housing unit density
P–interaction=0.0213
<£18,000
£18–30,999
£31,000–51,999
>£52,000
Odds of social isolation
Quartiles of housing unit density

Figure 1. Associations of residential density within 1 kilometer street catchment with loneliness and social isolation by sex, employment status and household income.

Models adjusted for socio-demographic covariates (age, sex, highest educational qualification, employment status, household income), plus lifestyle and risk factors (number of children, MET minutes per week for walking, weekly usage of mobile phone in past 3 months, smoking status, BMI, cardio-metabolic risks, and doctor-diagnosed nerves, anxiety and depression), built environment exposures (street-level physical walkability, density of public transport, traffic intensity in the nearest road, and mean street distance to destinations) and physical environment (terrain variability and residential greenness). P-values indicated significance of interaction between categories (quartiles) of residential density and population subgroups stratified by sex, employment status and household income. N for the fully-adjusted model for loneliness was 204,188 and for social isolation was 209,519. The vertical rectangles indicate the estimates of odds ratios while the error bars indicate 95% CIs.

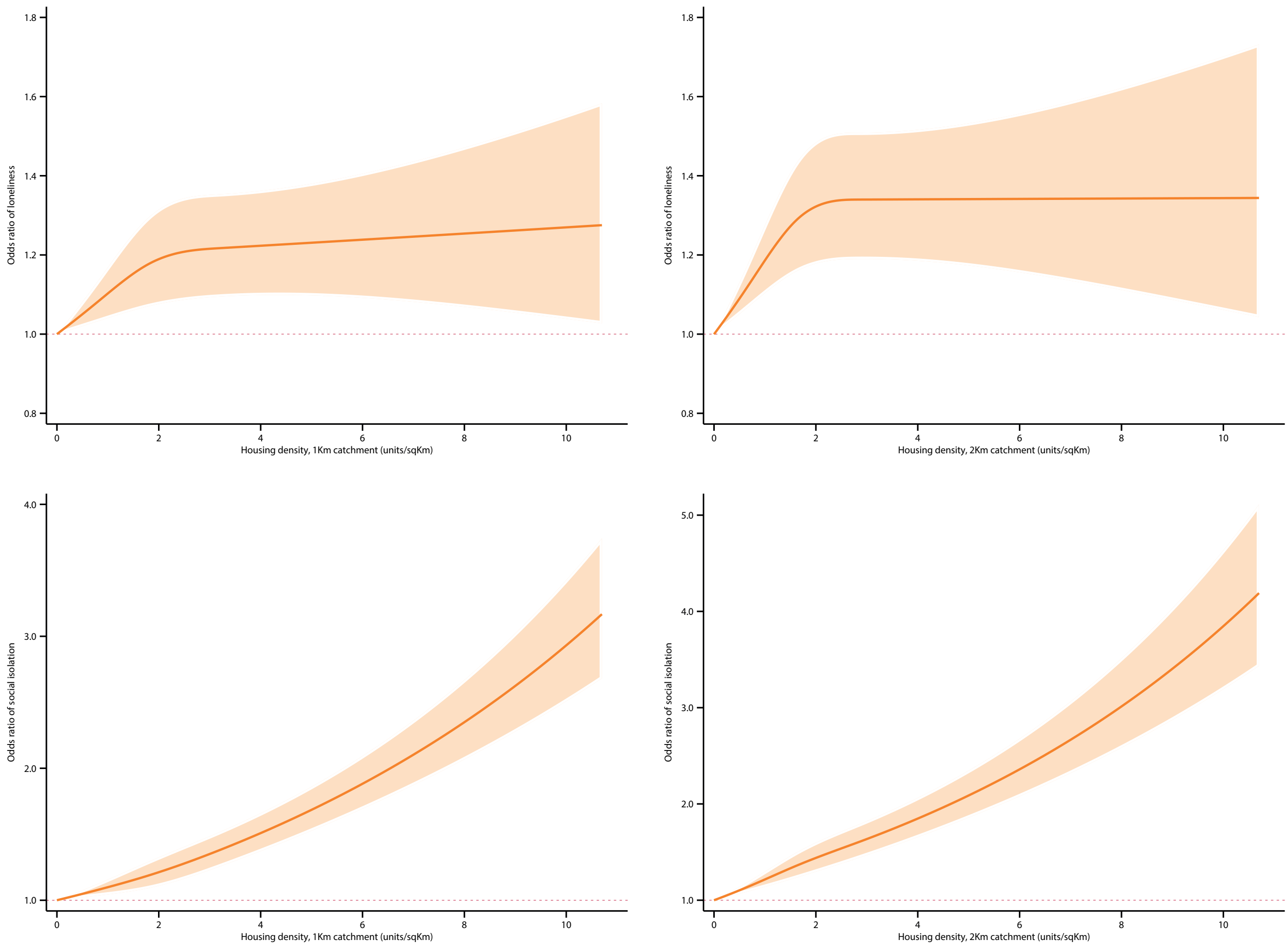


Figure 2. Non-linear restricted cubic spine models of associations of residential density measured at 1 and 2 kilometres with loneliness and social isolation.

The continuous line represents the estimated OR for loneliness and social isolation while the shaded regions indicate 95% CIs. Models adjusted for socio-demographic covariates (age, sex, highest educational qualification, employment status, household income), plus lifestyle and risk factors (number of children, MET minutes per week for walking, weekly usage of mobile phone in past 3 months, smoking status, BMI, cardio-metabolic risks, and doctor-diagnosed nerves, anxiety and depression), built environment exposures (street-level physical walkability, density of public transport, traffic intensity in the nearest road, and mean street distance to destinations) and physical environment (terrain variability and residential greenness). N for the fully-adjusted model for loneliness was 204,188 and for social isolation was 209 519.

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Author contributions

CS, CW, KYL and JG conceived the study. KYL, CS, CW and SK designed the study. KYL and SK conducted with the literature review. CS, SK and CW designed and developed the built environment metrics used in the study. KYL and CS cleaned the data and performed the statistical analyses. KYL developed the first draft of the paper. All authors commented on the draft and contributed to redrafting and interpretations. KYL was the lead researcher of the study.

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