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Systematic Review of the Associations between Transmission of COVID-19 or Other Respiratory Viruses and Population Density or Other Features of Neighbourhood Design

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Title

Systematic Review of the Associations between Transmission of COVID-19 or Other Respiratory Viruses and Population Density or Other Features of Neighbourhood Design

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SYSTEMATIC REVIEW OF THE ASSOCIATIONS BETWEEN TRANSMISSION OF COVID-19 OR OTHER RESPIRATORY VIRUSES AND POPULATION DENSITY OR OTHER FEATURES OF NEIGHBOURHOOD DESIGN

ABSTRACT

Background

Living in compact neighbourhoods that are walkable, well connected, have accessible green space and good access to amenities and public transport can bring benefits for physical and mental health. The Scottish Government is promoting the development of '20-minute neighbourhoods' in Scotland. These are neighbourhoods with easily accessible facilities within walking distance of homes. However, the Covid-19 pandemic has raised concern that the higher dwelling density needed to sustain 20-minute neighbourhoods could contribute to transmission of Covid-19 and other respiratory infections. Studies of population density and Covid-19 transmission have reached contradictory results and have often studied population density at large spatial scales. A better understanding of the links between respiratory viral transmission and population density and other aspects of neighbourhood design is needed to inform the development of Scottish planning policy.

Objectives

We aimed to identify, appraise and synthesise available evidence on links between transmission of respiratory viruses, including Covid-19, and dwelling or population density and other features of neighbourhood design. We restricted our review to quantitative empirical studies considering these characteristics at neighbourhood, sub-city or city level.

Methods

We conducted comprehensive, systematic electronic searches in six English and two Chinese databases to identify studies, up to 15th October 2020, which assessed the association between transmission of Covid-19 or other respiratory viruses, and population density and/or other features of neighbourhood characteristics. We supplemented this by reviewing reference lists and forward citation tracking. After titles, abstracts and subsequent full text screening, all eligible studies were quality assessed and given a GRADE level. The high level of heterogeneity of the studies did not allow for statistical analysis and therefore narrative analysis was employed to summarise findings.

Results

Database searches identified 1884 papers after de-duplication, and a further 6 through citation tracking. Of those, 21 papers met the inclusion criteria and were reviewed. Most studies reported evidence from USA or China, with one from Israel and one from the UK. The quality of the studies was low (n=5) or very low (n=16). Fifteen papers studied associations with Covid-19; six considered other respiratory infections. Most were ecological studies. Adjustment for confounding variables ranged from possible over control to no adjustment at all. There was inconsistency in primary and secondary outcomes.

Twenty studies analysed links with population density, one of which also considered housing density. These reported conflicting findings relating to population and housing density. Thirteen suggested a positive association between transmission and density, seven a negative association but several of these were not statistically significant, and the quality of the studies means overall findings should be treated with extreme caution. The studies considered a range of other neighbourhood characteristics including walkability; land use mix; building scale and other housing features; density of or distance to schools and other services; and markers of urban quality. Only a small number of studies investigated each of these, using differing measures, and their findings were inconsistent.

Conclusions

This review found no convincing evidence of a link between population density and transmission of Covid-19 and other respiratory infections. Although the possibility of an association cannot be ruled out, the current evidence does not suggest a need to change the current Scottish Government policy of support for the '20-minute neighbourhood' concept. Similarly, no clear conclusion can be drawn about any association between other characteristics of neighbourhood design and transmission of respiratory infection, including Covid-19. Further multi-disciplinary research using appropriate, sophisticated designs, is needed to allow a better understanding of links between neighbourhood characteristics and transmission of respiratory infections.

INTRODUCTION

The design of the places where people live has significant effects on health and wellbeing, through several pathways (Giles-Corti et al. 2016). A recent systematic review found positive impacts on mental and physical health associated with living in areas that were walkable and well connected, had accessible green space, good access to amenities and public transport, and fewer markers of poor quality such as noise, litter, crime and poor lighting (Ige-Elegbede et al. 2020). In recent years there has been growing recognition of potential health and sustainability benefits arising from a 'compact city' approach. This is defined as a city with short distances, increased residential density, mixed land use, accessible public transport and a well-connected urban form that encourages walking and cycling (Stevenson et al. 2016). A multi-country study of adults in 14 cities found increased physical activity associated with living in neighbourhoods with higher density of dwellings, intersections, public transport and parks (Sallis et al. 2016). A modelling study of six cities (Melbourne, Sao Paolo, Delhi, London, Boston, Copenhagen) predicted reductions in cardiovascular disease, respiratory disease and diabetes from changing to a more compact urban form (Stevenson et al. 2016). These findings have led to calls to 'reclaim city space for people', with a shift from developments characterised by urban sprawl towards creation of urban spaces that are active, liveable, inclusive and sociable, to achieve benefits for health and sustainability (Kleinert and Horton 2016).

The Scottish Government has recognised potential benefits of compact cities for health, sustainability and local economies, and is supporting the concept of the '20-minute neighbourhood' in the 2020/21 Programme for Government (Scottish Government 2020). These are defined as 'liveable, accessible places, with thriving local economies, where people can meet their daily needs within a 20 minute walk' (Scottish Government 2020). The City of Edinburgh Council is developing its City Plan, which aims to deliver 40,000 to 50,000 new homes in the city over the next 10 years (City of Edinburgh Council 2020). In line with Scottish Government ambitions, it is developing a policy of '20-minute neighbourhood' developments. One of the requirements to enable this is increased dwelling density from 30-35 dwellings per hectare, which is typical of recent greenfield developments, to at least 65 dwellings per hectare. These higher densities are needed to ensure critical mass to support local services and amenities but are still lower than many current areas of the city (for example, Gorgie with predominantly flats has 300 dwellings per hectare, and Bonnington has a mix of flats, townhouses and colonies at 100-200 dwellings per hectare). A rapid scoping assessment (Douglas and Beautyman 2020) identified potential positive impacts for health from the 20-minute neighbourhood scenario, but highlighted the importance of ensuring other aspects are in place including good infrastructure, services and design quality.

The Covid-19 pandemic has highlighted further the importance of local neighbourhoods for health and wellbeing, as people have been asked to stay home and restrict travel. It also raises questions about whether, and how, neighbourhood design might impact on transmission of communicable disease including Covid-19. In particular, there have been concerns that the higher population and dwelling densities needed to support the '20minute neighbourhood' might facilitate transmission of SARS CoV2 by increasing levels of face to face interaction (Sharifi and Khavarian-Garmsir 2020). However, studies of the association between population density and incidence of Covid-19 have shown conflicting findings.

Results of studies comparing global cities (Bai et al. 2020; Kang et al. 2020) suggest that population density does not account for differences in the incidence of Covid-19, as Asian cities with higher densities had lower incidence than Western cities with lower density. This could indicate that differences in policy and public responses between these settings are more important than differences in population density. Studies of the association between population density and spread of Covid-19 in Chinese provinces have reported conflicting findings (Lin et al. 2020; Sun, Zhang, et al. 2020). Two studies of Japanese provinces found an association between density and transmission of Covid-19, but compared small numbers of provinces (Kodera, Rashed, and Hirata 2020; Rashed et al. 2020). There have been several studies of counties in the USA, using differing methods and measures to assess Covid-19 transmission. Some have reported a positive correlation with population density at county level (Behnood, Mohammadi Golafshani, and Hosseini 2020; Sy, White, and Nichols 2020; You and Pan 2020; Zhang and Schwartz 2020) but this finding is not consistent (Hamidi, Ewing, and Sabouri 2020). These studies all vary in quality. Some report cumulative number of cases, rather than incidence rate and most do not control for socioeconomic or other likely confounders. A study of 'hot spots' at a smaller spatial scale within New York and Chicago found that high density areas were less likely to be hot spots and household size was a key determinant in both cities (Maroko, Nash, and Pavilonis 2020). European studies at provincial or county scale similarly give conflicting findings. Population density was not found to be associated with Covid-19 mortality in Italian provinces (Perone 2021) or Netherlands counties (Boterman 2020). However two studies of English local authorities found a positive association between population density and Covid-19 mortality (Bray, Gibson, and White 2020) and incidence at the end of March 2020 (Tammes 2020) although in the latter study the highest density quartile had the lowest incidence by the end of April.

It is difficult to interpret the relevance of studies that have considered population density at large spatial scales, which are likely to contain heterogeneous areas of differing density within them. The same population density may also reflect different morphologies that could have different impacts on transmission (Fezi 2020). Other aspects of neighbourhood design, such as connectivity, housing type and land use mix may impact on transmission, by enabling or hindering physical distancing, but there is less evidence so far on these factors (Sharifi and Khavarian-Garmsir 2020). All of these associations may be confounded by factors such as poverty, age, comorbidity, residents' occupations, household structure and overcrowding, travel and commuting patterns, and so these should be considered in the analyses.

A better understanding of the links between housing and population density and other aspects of neighbourhood design is needed to inform the development of planning policy in Edinburgh and other Scottish Local Authorities. We undertook a systematic review of the association between population density, and other aspects of neighbourhood design, and transmission of respiratory viruses including SARS CoV2. We restricted our review to studies that consider these characteristics at neighbourhood, sub-city, or city level.

METHODS

The research question for this review was: *How is transmission of respiratory viruses, including Covid-19, affected by population density and other features of neighbourhood design?*

We restricted our review to studies that consider these characteristics at neighbourhood, sub-city, or city level. A study protocol for this systematic review was published on Prospero (Douglas et al. 2020). This was developed in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols statement (PRISMA) (Moher et al. 2009).

Search strategy

We developed a search strategy using terms relating to neighbourhood; infectious respiratory disease; and relevant study designs. We identified initial search terms from indicator papers and test searches. We used the bibliographic databases Medline, Embase, Web of Science, Scopus, ASSIA, Avery Index to Architectural Periodicals, Wanfang and CNKI. Two members of the team who are native Chinese speakers (ZS and XZ) developed Chinese search terms adapted from the English search. We applied no restriction on language or date of studies. Studies in languages other than English and Chinese were reviewed against inclusion/criteria by colleagues with relevant language skills. We piloted the draft search strategy on all the databases before finalising it. We ran the searches on 12th and 15th October 2020. The final search strategies are detailed in Appendix 1. We also checked the reference lists of included papers and performed forward citation checking to identify other relevant studies.

Screening and selection of studies

Search results were imported into the systematic review system, Covidence. All team members took part in title and abstract screening. For each paper, two reviewers independently screened titles and abstracts against the predefined eligibility criteria (Table 1 below), and a third reviewer screened conflicts to determine whether to proceed to full text screening. Full text papers were similarly reviewed independently by two reviewers. Disagreements were discussed to reach consensus. A PRISMA flowchart, (Figure 1, Result section) displays the results of the search and screening process.

Table 1: Eligibility criteria

	Include	**Exclude**
Populations	Human populations – any age, sex or ethnic group	Studies of infections in animals
Condition	Viral respiratory infectious diseases Covid-19	Studies of non-respiratory or non-infectious diseases
Exposure	Studies comparing transmission by aspects of housing/neighbourhood design: Dwelling or population density at neighbourhood/city level	Overcrowding in home or household composition (bedroom number, number of adults) Studies concerned with building materials, air and water quality

	Housing type Street connectivity or walkability Land use mix Features of 'smart urbanism' or '15 - 20 minute neighbourhoods'	Design of healthcare, education or transport systems only Studies assessing social mobility or effects of social distancing
Outcome	Proxies for transmission: Incidence, prevalence, test positivity, hospital admission, mortality	Studies with no measure of transmission
Study type	Studies providing empirical quantitative data	Opinion pieces, modelling studies predicting infection transmission without new empirical data, qualitative studies and reviews (retained the latter two types of study for separate analysis and background)
Context	Studies based in high/middle income countries	Studies based in low income countries

Data extraction and management

We used the data extraction facility on Covidence to extract data from included papers. For each paper, two team members independently extracted data then agreed the final dataset by consensus. We piloted the data collection form by using it for one randomly selected study before finalising it. Data were extracted on the study (author, year, study design, country, time period studied), neighbourhood (setting, measures of design), respiratory infectious disease (type, outcome) and main findings (analysis metric, effect size, covariates included in analysis).

Quality and risk of bias assessment

Two team members appraised each study, with differences resolved by consensus. We used the relevant CASP checklists for cohort and case/control studies. We adapted a checklist for ecological studies originally for another review (Betran et al. 2015). We then graded the quality using the Grades of Recommendation, Assessment, Development and Evaluation (GRADE) system (Guyatt et al, 2008). We used the approach recommended by Usher Network for COVID-19 Evidence Reviews (UNCOVER) as follows: observational studies are given an initial grading of low, then upgraded if multiple studies show consistent results or downgraded if quality appraisal identified potential for bias in the findings.

Synthesis

All eligible studies were summarised and compared in terms of their characteristics (respiratory disease, exposures, outcomes and effect estimates). We planned to conduct a narrative review but consider meta-analysis if three or more studies collected data on the same exposure and outcome. However, due to significant heterogeneity, predominantly in exposure and/or outcome characteristics, narrative analysis of all eligible studies was conducted.

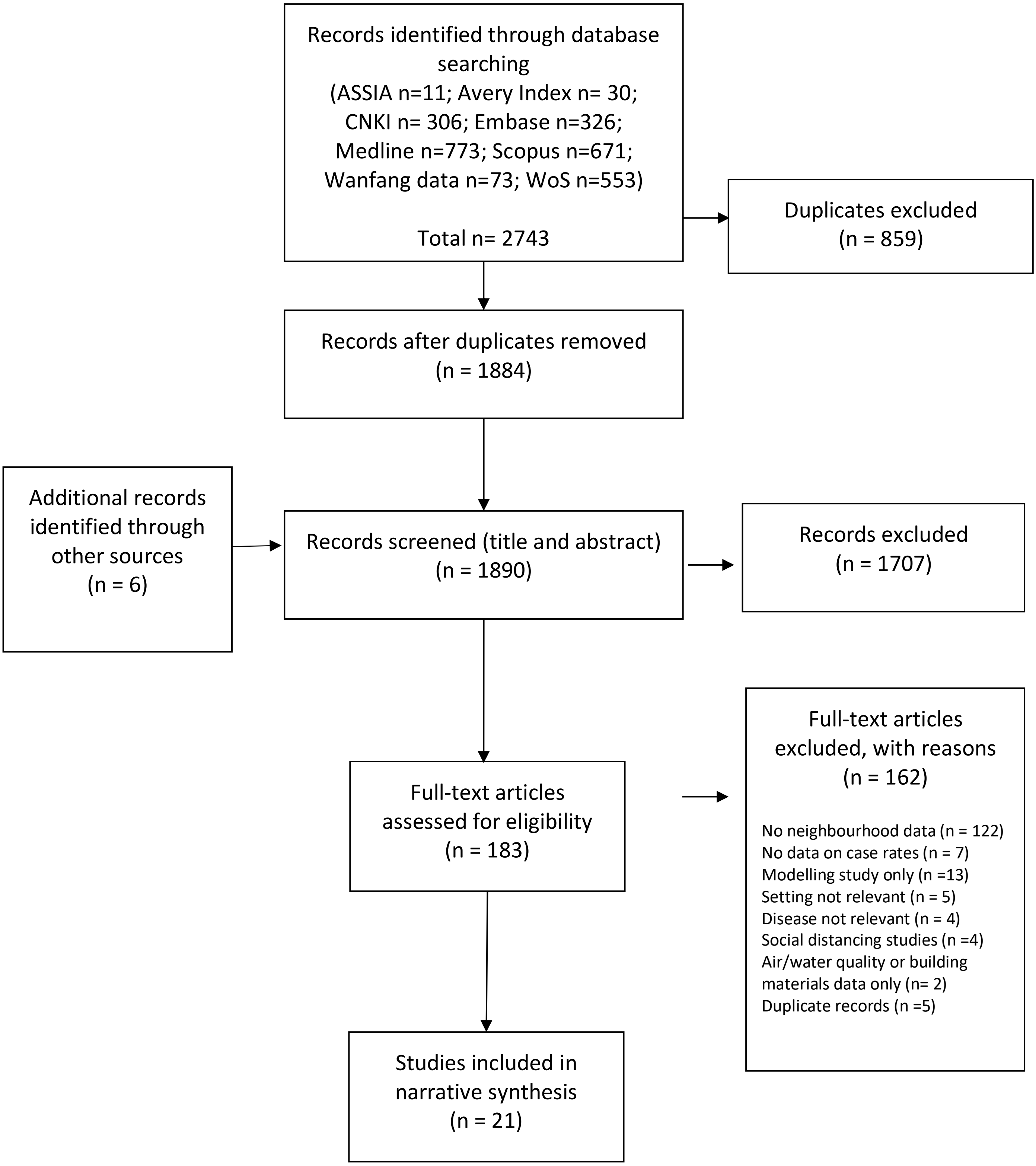
RESULTS

Study selection

The database searches identified a total of 2,743 papers. Six further papers were identified by citation tracking. After removal of duplicates, 1,890 titles and abstracts were screened. Full texts of all potentially relevant studies (n=183) were screened, 162 of which were excluded, and the reasons were noted. The commonest reason for this was that the paper did not include data on neighbourhood design or population density at city or sub-city level. We also excluded seven papers because they were ecological studies that used the total number of positive cases in an area, rather than a rate, as the outcome measure. Twenty one studies were eligible for inclusion in the systematic review.

The PRISMA flowchart below displays the results of the search and screening process.

Figure 1: PRISMA flow diagram of publications selection, screening and appraisal



Included papers

We included a total of 21 papers: 13 from USA, six from China, one from Israel and one from the UK. Fifteen of these studied Covid-19, most in the whole population but two were in pregnant women. The remaining six studied other respiratory infections including influenza, SARS, lower respiratory infections in children, and *Haemophilus influenzae* in children. All the included papers except one (Jin et al. 2020) considered links with population density but only one also considered housing density (houses per mile^2) (DiMaggio et al. 2020). Twelve studies considered other aspects of neighbourhood design, including the number of housing units per building, residential building scale, walkability, land use mix, proximity and density of various facilities. Two (Gu et al. 2020; Vahidy et al. 2020) studies aimed to explore other factors such as racial inequalities in transmission, and used population density as a covariate. In some papers the measure used for population density was not defined. Where given, the definition of population density varied, with different studies using persons per metre^2, km^2, mile^2, acre, and Hectare.

Fourteen were ecological studies comparing case rates between geographical areas. Seven studies compared individuals who tested positive with a control group, usually people who tested negative. Most of the studies of Covid-19 were conducted early in the pandemic when the number of positive cases was lower, those identified were likely to have more severe symptoms, and case definitions may have varied. The level of heterogeneity of the papers was high with different settings, outcomes and analysis metrics.

Below we presented summary of all included papers and findings relating to population density, followed by a summary for different aspects of neighbourhood design. The amount and clarity of the summary below reflects discrepancies in precision of reporting of individual studies, specifically methodological and analytical information available at the time of this review.

Studies of Population Density

Across the studies of Covid-19 in all settings, 13 reported a positive association with population density and seven a negative association. (Tables 2, 3, 5 and 7) Several of these findings were not statistically significant and/or were small effects. The quality of the studies was low or very low. A few simply reported figures for population density and Covid-19 rates that were unadjusted for any covariates. Some others presented statistical models that included population density and spatial features of geographical areas, but no data on the characteristics of the people living there that might affect their risk. These limitations mean that the findings should be treated with caution.

Of the studies of other respiratory infections, six reported a positive association with population density and six reported a negative association (Table 4 and Table 6). The quality of these studies was also low or very low.

Further details of the studies are discussed below, by setting, type of study and outcome.

USA Covid-19 studies
Ten USA based studies investigated links between population density and Covid-19, five ecological and five studies with individual level data (Table 2 and Table 3, respectively). Most USA studies adjusted for age, sex, and race. Several included measures of poverty or household income, unemployment, education, or insurance status. Other covariates included household size and/or overcrowding and composite measures of neighbourhood disadvantage. One included working from home and internet access (Bryan et al. 2020). Some, but not all, included comorbidity. This is important because in some places in the early stages of the pandemic, testing was restricted and so people with severe disease were more likely to have been detected.

Of the five USA based ecological studies (Table 2), two studies (DiMaggio et al. 2020; NYU Furman Centre 2020) compared 177 zip codes in New York, one (Credit 2020) included 54 zip codes in Chicago and 177 in New York, one (Bryan et al. 2020) compared 795 census tracts in Chicago, and the last (Nguyen et al. 2020) compared 7,625 zip codes across 20 states. The studies measured the cumulative rates in each area up to a set date ranging from April to July 2020. Most used confirmed cases as the outcome, except the Chicago study (Bryan et al. 2020), which used mortality, and so only included the most severe cases. The studies used various government, county and state resources for data on cases, which may have had differing levels of ascertainment. They used different metrics for analysis including regression coefficient, rate ratio and incidence density ratio – Table 2 shows the metrics used in each study. The multi-state study (Nguyen et al. 2020) found a positive association with population density with rate ratio varying between 1.01 and 1.04 in the models shown. Of the studies that included New York, one reported a positive, albeit statistically non-significant association (DiMaggio et al. 2020), one found a negative association that was not statistically significant (Credit 2020). The final New York study was a descriptive study, with no adjustment for confounders and reported that areas with higher numbers of confirmed COVID-19 cases had lower population density (NYU Furman Centre 2020). The ecological study from Chicago (Bryan et al. 2020) used mortality from Covid-19 as the outcome and found an inverse association with population density. However, the significance of this association diminished after adjustment for statistically associated covariates and therefore should be interpreted with caution.

Of the five USA studies at individual level (Table 3), two focused on pregnant women who were tested for SARS CoV-2 (the virus that causes Covid-19) when they attended a labour and delivery unit in New York (n=396) (Emeruwa et al. 2020) or Georgia (n=1,882) (Joseph et al. 2020). One of these found a positive association with population density (Joseph et al. 2020) whereas the other found a negative association (Emeruwa et al. 2020). However, these studies only reported bi-variate regression results, therefore it is not clear if this association would persist after adjustment for factors associated with COVID-19 positivity.

The other three individual level studies focused on people tested in Eastern Massachusetts (n=57,865) (Cromer et al. 2020) Greater Houston area (n=20,228) (Vahidy et al. 2020) and Michigan (n=5,698) (Gu et al. 2020). These recorded the proportion of positive results from those tested, with the longest study period being 1st February to 21st June (Cromer et al. 2020). All three reported odds ratio values with a positive direction of effect of population density. The Massachusetts study (Cromer et al. 2020) reported a fully aOR 1.14 [95% CI 1.03 to 1.27] and the Michigan study (Gu et al. 2020) reported aOR 1.07 [95% CI 1.03-1.11] for test positivity among those tested. The study from Greater Houston (Vahidy et al. 2020) set out to study mediators of racial disparities. They concluded that population density indirectly mediated the effect of non-Hispanic Black race (OR 1.03 [95% CI 1.01 to 1.05]) and Hispanic race (OR 1.02 [95% CI 1.01 to 1.02]). However, this increase in the odds is small compared to the increased odds for these racial groups in their final fully adjusted model, which included other covariates but not population density (non-Hispanic Black race aOR 2.23 [95% CI 1.90 to 2.60], Hispanic race aOR 1.95 [95% CI 1.72 to 2.20]).

USA non Covid-19 studies

We found three USA based studies on respiratory infectious diseases other than COVID-19, which all used an ecological approach to study the relationship between hospitalisation or mortality rates and population density at the census tract level (Table 44). One reported lower respiratory infections in children under 5 years in Arizona from 2005 to 2009 (Lothrop et al. 2017), one investigated deaths from the 1918 influenza pandemic in Chicago (Grantz et al. 2016) and the last studied influenza hospitalisations between 2007 and 2014 in Tennessee (Sloan et al. 2015). Two of these reported a statistically significant negative association with population density (Grantz et al. 2016; Lothrop et al. 2017). The third (Sloan et al. 2015) reported a statistically significant increase in hospital admissions for influenza in the highest density areas but this study adjusted only for age and it is unclear if the association would persist after adjusting for other factors associated with influenza hospitalisations.

China Covid-19 studies

Four studies of Covid-19 based in China were included in this review (Table 5), but only three reported the association with population density (Huang et al. 2020; Liu, Yuan, et al. 2020; You, Wu, and Guo 2020). These three studies were all ecological in design. The units of analysis ranged in size from tertiary planning units in Hong Kong, which have average population size 25,000 people, to cities in Hubei province with population size between 76,000 and 9.7 million inhabitants. There is likely to be significant heterogeneity of population density and other characteristics within these areas. They all assessed only geographical features and did not adjust for the characteristics of people living in each area. All three reported a statistically significant positive association with population density. However these findings should be interpreted with caution as it is unclear if these associations would persist in models considering covariates relating to residents of the areas.

China non Covid-19 studies

There were two studies from China of other respiratory infections, one on influenza H1N1 (Xiao et al. 2014) and one on SARS (Liang and Mi 2003) (Table 6). The influenza H1N1 study was a case control study and the SARS study was an ecological descriptive study, describing the incidence in urban, suburban and far suburban settings. Their findings suggest a positive association with population density, but neither of these studies used models that allowed adjustment for characteristics of residents in each area, impacting on the robustness of these findings.

Studies in other countries

There were two studies from countries other than USA or China, both ecological (Table 7).

An Israeli study of Covid-19 (Birenbaum-Carmeli and Chassida 2020) found a positive association with population density, reporting that an increase of 100 persons per km^2 raised Covid-19 case rate by 2.4 cases per 100,000 persons. They also considered Jewish and Arab communities separately and found that population density was positively associated with Covid-19 case rates in both types of community, both at nominal level of statistical significance. The study found the counterintuitive results that higher proportions of older people and lower socioeconomic status were both statistically significantly associated with lower rates of Covid-19. They attributed these to various factors including large families with children causing spread of infection, but do not adjust for the child population in their analysis of population density.

We found only one study from the UK that met our inclusion criteria (Olowokure et al. 2003). It reported on *H. influenzae* type b in children under 5 years, West Midlands, before and after the introduction of Hib vaccine in the 1990s. In both time periods before and after the vaccine, they found a negative association with population density. The trend was statistically significant in each case, but findings were unadjusted for covariates and may be confounded by other factors.

Studies of other neighbourhood characteristics

The studies considered a diverse range of neighbourhood characteristics as well as population/dwelling density. These findings are summarised below.

Housing units per building, scale and type

Seven studies reported associations with residential units per building, building scale and housing type. Four of these, all from the USA (Bryan et al. 2020; Cromer et al. 2020; Emeruwa et al. 2020; NYU Furman Centre 2020), studied the association between Covid-19 rates and the number of residential units per building, finding either no association or a negative association with the number of units per building. The authors of one of these papers, from Chicago (Bryan et al. 2020) suggested that this may be because affluent residents live in some densely populated areas containing buildings with a large number of units. Two studies from China considered associations between Covid-19 and building scale (You, Wu, and Guo 2020) or building height (Huang et al. 2020), which may be indicators of higher housing density. These reached conflicting results. The final study of hospitalisations for respiratory infection in children (Lothrop et al. 2017) found a positive association with attached homes and mobile homes, but this could be confounded by socio-economic factors.

Walkability, active commuting and land use mix

Three studies considered associations with indicators of walkability, active commuting or land use mix. These reached conflicting results. The study of zip codes in Chicago and New York (Credit 2020) found that zip codes with higher levels of active commuting had lower rates of confirmed Covid-19, including the fully adjusted models. This just reached statistical significance in New York but was not statistically significant in Chicago. In contrast, the larger study of over 7,000 zip codes in 20 states found that indicators of walkability and mixed use both increased the rate of Covid-19 whereas single lane roads reduced the rate. The Hong Kong study (Huang et al. 2020) found that land use mix was negatively associated with the incidence of confirmed Covid-19.

School density/proximity

Three studies considered associations with proximity to or density of schools. A study from New York (DiMaggio et al. 2020) found that Covid-19 incidence density ratio was not statistically significantly associated with school density. Two studies from China considered the association between proximity or number of educational facilities and Covid-19 (Jin et al. 2020) or H1N1 influenza (Xiao et al. 2014). Both found a positive association but used a case control design with geographical controls. This design may introduce bias as, given equal risk across the population, highly populated areas will have more cases and are also likely to have more facilities.

Other facilities density/proximity

Three studies, all based in China, studied the association with density of, or distance to, various commercial facilities. Their findings are inconsistent. The Hong Kong study (Huang et al. 2020) found no statistically significant association, whereas the other two studies (Jin et al. 2020; Xiao et al. 2014) found a positive association. All three studies have methodological limitations that mean results should be treated with caution.

Urban quality

Finally, three ecological studies considered other indicators of physical urban quality, with inconsistent findings. Three studies of Covid-19 considered the association with greenspace. The multi-state USA study (Nguyen et al. 2020) found a negative association but a Wuhan study (You, Wu, and Guo 2020) reported a positive association and the Hong Kong study (Huang et al. 2020) found no statistically significant association.

The study from Wuhan (You, Wu, and Guo 2020) found a positive association with construction land. The USA study (Nguyen et al. 2020) also found a positive association with indicators of physical disorder such as wires and dilapidated buildings.

SUMMARY TABLES BY TYPE OF STUDY, RESPIRATORY INFECTIOUS DISEASE, AND COUNTRY

Table 2: Ecological studies of Covid-19 in the USA

Author Year	**Setting and Design**	**Measure of neighbour-hood design**	**Primary outcome(s)**	**Direction of effect for population density**	**Reported results (95% confidence interval)**	**Adjusted covariates**	**Quality (GRADE)**
Bryan 2020	Chicago Ecological study 795 census tracts Chicago total population is 2.7 million	Population density (per mile^2) % units in buildings with 20+ units	Mortality rate – deaths recorded as caused by Covid-19 Mar 16th to Jul 22th 2020 2514 deaths	↓ns	Rate ratio Population density: Bivariate: 0.82 (0.78-0.87) Adjusted: 1 (0.0-1.0) % units in buildings with 20+ units: Bivariate: 0.76 (0.71-0.80) Adjusted: 1 (0.99-1.00)	Age Gender Race Poverty Comorbidity – mortality from heart disease, diabetes, nephrotic, tobacco related Crowded living conditions Transport Work from home Internet access Educational attainment Healthcare access Air quality 33 covariates, all at census tract level	Very Low
Credit 2020	New York and Chicago Ecological study Chicago: 54 zip code tabulation areas New York: 177 zip code tabulation areas Total populations Chicago 2.7million NY 8.3million	Population density (per m^2) Percent pedestrian and bike commuters Hospital accessibility Percent food desert tracts	Confirmed cases per head up to 1st May 2020	↓ ns	Regression coefficient Chicago Population density: -26.6 (13.9) p=0.06 Active commuting: -0.47 (0.41) p=0.28 New York Population density: -1.06 (1.37) p= 0.4 Active commuting: -0.56 (0.29) p=0.05	Age Race Occupation in Healthcare Overcrowding Median Income Testing rate	Very Low

Author Year	Setting and Design	Measure of neighbour-hood design	Primary outcome(s)	Direction of effect for population density	Reported results (95% confidence interval)	Adjusted covariates	Quality (GRADE)
DiMaggio 2020	New York Ecological study 177 zip code tabulation areas	Population density Housing density School density All (per mile^2)	Positive tests per 10,000 and proportion of tests positive up to 22nd April 2020	↑ ns	Incidence density ratio Housing density: Unadjusted: 2.0 (1.2-3.2) Multivariable:1.08 (0.65-1.78) Population density: Unadjusted: 1.5 (1.1-2.2) Multivariable: ns in model, not reported	> 65 yrs. Black/African American COPD Heart disease	Low
Nguyen 2020	US states Ecological study 7625 zip codes in 20 states	Definition of population density not stated Indicators of: Walkability Urban developmnt Physical disorder	Cases per 100,000 up to 21st June 2020	↑	Rate Ratio Population density: varies by model, range 1.01 to 1.04 Non-single-family home: 1.21 (1.16-1.25) Sidewalks: 1.40 (1.34-1.46) Crosswalks: 1.14 (1.10-1.18) Visible wires: 1.08 (1.03-1.13) Dilapidated building: 1.03 (0.99-1.08) Single lane roads: 0.90 (0.86-0.94) Green streets: 0.96 (0.92-1.00)	Age Race Household Size Household Income Poverty Rate Education Civilian employment	Very low
NYU Furman Centre 2020	New York Ecological study zip codes – number not stated	Population density (per mile^2) Housing ≥ 10 units	Zip code quintiles based on number of cases per 1,000 people on 7th April 2020	↓	Population density Highest incidence quintile: 25,082 4th quintile : 20,144 3rd quintile : 29,050 2nd quintile : 47,845 Lowest quintile : 48,067 Percent share of housing ≥ 10 units Highest incidence quintile: 41.7% (±0.6%) 4th quintile : 44.9% (±0.5%) 3rd quintile : 47.7% (±0.5%) 2nd quintile : 71.0% (±0.6%) Lowest quintile : 63.7% (±0.6%)	None	Very Low

↑: Increase in effect with increasing population density; **↓:** Decrease in effect with increasing population density; **ns:** not significant

Table 3: Individual level studies of Covid-19 in the USA

Author, Year	Setting and Design	Measure of neighbour-hood design	Primary outcome	Direction of effect for population density	Reported results (95% confidence interval)	Adjusted covariates	Quality (GRADE)
Cromer 2020	Integrated health care system in Eastern Massachusetts Cohort study of adults who presented for testing, excluded people employed in healthcare system Sample size: 57,865 tested 9,839 positive cases	Population density (not defined, Log Population Density used in models) Residential units per building For census tract of residence	Positive SARS CoV 2 test: 1st Feb to 21st June Hospital admission among those positive Deaths among those in hospital	↑	<u>Odds Ratio</u> <u>Population density</u> *Positive tests:* Base Plus: 1.24 (1.14-1.36) Full Model: 1.14 (1.03 - 1.27) *Hospitalisation:* Base Plus: 1.24 (1.04-1.51) Full Model: 0.99 (0.80 - 1.24) *Deaths:* Base Plus: 1.14 (0.86-1.51) Full Model: ns not included <u>Housing units per building</u> *Positive tests:* Both models: ns *Hospitalisation:* Base Plus: %1 unit 0.52 (0.36-0.74) %>2 units 2.08 (1.42-3.04) >3/5/10/20/50 units ns Full model %>2 units 1.83 (1.01-3.31) *Deaths:* Both models: all ns	<u>Base plus model – adjusted for individual level covariates</u> Age Sex Race Language Insurance <u>Full model - also adjusted for other census tract variables</u> Income Poverty Education Employment Household crowding Household occupancy Transport	Low

Author Year	Setting and Design	Measure of neighbour-hood design	Primary outcome	Direction of effect for population density	Reported results (95% confidence interval)	Adjusted covariates	Quality (GRADE)
Emeruwa 2020	New York pregnant women attending Presbyterian/ Columbia University Irving Medical Center or Allen Hospital maternity units for delivery Cross sectional study Sample size: 396, 71 positive	Population density (no definition) Number of residential units per building By neighbourhood tabulation area of residence	Positive SARS CoV 2 test: 22nd Mar to 21st April 2020	↓	% positive 2 units per building (10th percentile of units per building): 23.6% (17.6-29.5) 193 units per building (90th percentile): 9.2% (4.7-14.4) Interdecile Odds Ratio Population density: 0.70 (0.32-1.51) Buildings with more residential units: 0.34 (0.16-0.72) Buildings with higher assessed values: 0.29 (0.10-0.89)	None	Very low
Gu 2020	Michigan Medicine health system: people tested and random controls Retrospective cohort study Sample size: 5698 tested and 7168 non tested controls 1,139 positive	Population density (1000 Persons per mile ^{2}) By census tract of residence	Positive SARS CoV 2 test; Hospitalisation with Covid-19 diagnosis ICU admission with Covid-19 diagnosis 10th Mar to 22nd April 2020	↑	Odds Ratio Positive test v untested: 1.12 (1.08-1.16) Positive test v negative test: 1.07 (1.03-1.11) Hospitalised v not: 1.10 (1.01-1.19) ICU v not: 1.08 (0.99-1.19)	Age Sex Race BMI Smoking Alcohol Neighbourhood disadvantage score Comorbidity – composite score, respiratory, circulatory, cancer, diabetes, kidney, liver, autoimmune disease	Low

Author Year	Setting and Design	Measure of neighbour-hood design	Primary outcome	Direction of effect for population density	Reported results (95% confidence interval)	Adjusted covariates	Quality (GRADE)
Joseph 2020	Atlanta, Georgia: pregnant women in 2 hospitals admitted for delivery Retrospective cohort study Sample size: 1882, 77 positive	Population density In 2 bands By census tract of residence	Positive SARS CoV 2 test: 20 April -29 July 2020	↑	<u>Prevalence of positive test</u> Less dense 3.1 (2.0-4.2) More dense 5.1 (3.7-6.5) P=0.03	None	Very low
Vahidy 2020	Greater Houston Cross sectional analysis Sample size: 20,228, 1,551 positive	Population density (per mile^2) By zip code tabulation area of residence	Positive SARS CoV 2 test: 5th Mar to 31st May 2020	↑	<u>Unadjusted Odds Ratio</u> Percentile 1 reference lowest Percentile 2: 1.39 (1.22-1.57) Percentile 3: 1.05 (0.92-1.20) Percentile 4: 2.02 (1.79-2.28) Percentile 5 highest: 1.48 (1.31-1.68) <u>GSEM model for race mediated through population density</u>: Non Hispanic Black: OR 1.03 (1.01 to 1.05) Hispanic: OR 1.02 (1.01 to 1.06)	GSEM model adjusted for age and sex	Low

↑: Increase in effect with increasing population density **↓**: Decrease in effect with increasing population density **ns**: not significant

Table 4: Ecological studies of non-COVID-19 respiratory infections in USA

Author Year	Setting and Design	Measure of neighbourhood design	Primary outcome	Direction of effect for population density	Reported results (95% confidence interval)	Adjusted covariates	Quality (GRADE)
Grantz 2016	Chicago Ecological study 496 census tracts	Population density (per acre)	Influenza mortality per 1000 Reproduction number calculated from mortality From 26th Sept 1918 to 16th Nov 1918 7,971 deaths	↓	Mortality: <u>Risk Ratio</u> Univariate: 1.00 (0.99-1.002) Multivariate: 0.996 (0.994-0.997) Mortality decreased by 4.3% (95% CI = 3.1%, 5.5%) per 10% increase in population density R number: <u>Correlation coefficient</u> 0.29 (0.25- 0.31) p<.001 Weekly R number population density ns for 6 of the 7 weeks.	Age Illiteracy rate Homeownership rate Unemployment rate	Very Low
Lothrop 2017	Maricopa and Pima Counties, southern Arizona Ecological study Total population size 4.8 million people Emergency Dept (ED) visits: 826 census tracts Hospital admissions: 805 census tracts	Population density (per mile^2) Percent mobile homes Percent attached homes	Lower respiratory infections in children <5 yrs. Rates of ED visits and Hospital admissions From 2005 to 2009	↓	<u>Incidence Rate Ratio</u> <u>Population density</u> ED visits: Simple analysis: 1.05 (1.01-1.08) Multiple analysis: 0.94 (0.89 - 1.00) Admissions: Simple analysis: 0.80 (0.73-0.87) Multiple analysis: 0.50 (0.45 - 0.57) <u>Percent attached homes</u> ED visits: Simple analysis: 1.07 (1.05-1.09) Multiple analysis: 1.04 (1.02 - 1.06) Admissions: Simple analysis: 1.05 (1.01-1.10) Multiple analysis: 1.04 (1.00 - 1.08) <u>Percent mobile homes</u>	Socio-economic status Air pollution Overcrowding Gas heating Lacking plumbing Built before 1940 County	Very Low

Author Year	Setting and Design	Measure of neighbourhood design	Primary outcome	Direction of effect for population density	Reported results (95% confidence interval)	Adjusted covariates	Quality (GRADE)
Lothrop 2017 (cont)					ED visits: Simple analysis:1.05 (1.03-1.07) Multiple analysis: 1.03 (1.01 - 1.05) Admissions: Simple analysis: 1..10 (1.06-1.15) Multiple analysis: 1.04 (1.01 - 1.08)		
Sloan 2015	Middle Tennessee – Nashville and neighbouring counties Ecological study of census tracts Total population size 1.5 million Number of census tracts not stated	Population density (per mile^2, in 3 bands: low, medium and high)	Influenza hospital admissions per 100,000 person yrs. From Oct 2007 to April 2014 1743 hospital admissions	↑	Rate Ratio (RR), Rate Difference (RD) compared to low density RR for medium density 1.0 (0.8, 1.2) RD for medium density -0.3(-2.6, 2.1) RR for high density 1.3 (1.2, 1.5) RD for high density 4.7 (2.7, 6.8)	Age only	Very Low

↑: Increase in effect with increasing population density; **↓:** Decrease in effect with increasing population density; **ns**: not significant; **ED**: Emergency Department

Table 5: Studies of COVID-19 in China

Author Year	Setting and Design	Measure of neighbourhood design	Primary outcome	Direction of effect for population density	Reported results (95% confidence interval)	Adjusted covariates	Quality (GRADE)
Huang 2020	Hong Kong Ecological study 291 tertiary planning units	Population density (per km^2) Private residential density Commercial density Greenspace density All proportion of land for each use: Building height Transport density Land use diversity Sky view	Confirmed cases per 1000, locally transmitted cases only 27th Jan to 14th April 2020	↑	<u>Poisson regression coefficient</u> Population density: -4.00 (0.48) $p<.001$ Private residential density: 3.21 (0.74) $p<.001$ Land use diversity -1.13 (0.19) $p<.001$ Building height: 0.9 (0.37) $p=0.015$	Geographical features only	Very Low
Liu 2020	Hubei province Ecological study 17 cities	Population density (per km^2)	Covid-19 cases per 1000 Up to 16th April 2020	↑	<u>Exponential Regression Coefficient</u> All cities: $Y=1.195e^{0.002X}$, $R^2=0.77$, $p<0.005$ - Excluding Wuhan and Shennongjia: $Y=1.238e^{0.002x}$, $R^2=0.498$, $p<0.005$ –	None	Very Low

Author Year	Setting and Design	Measure of neighbourhood design	Primary outcome	Direction of effect for population density	Reported results (95% confidence interval)	Adjusted covariates	Quality (GRADE)
You 2020	Wuhan Ecological study 13 districts	Population density (10,000 persons per km^2) Aged population density (per km^2) Construction land area proportion Average building scale Public green space density Tertiary industry Retail sales Hospital Density	Confirmed cases per 10,000 people Up to 22nd Feb 2020	↑	Pearsons correlation analysis and Spatial Regression Analysis Population density Pearson's R = 0.81 p=0.001 Spatial lag model estimate: 38.338 p<.01 Aged population density Pearson's R = 0.84 p<0.001 Spatial lag model estimate: 0.021 p<.05 Construction land proportion Pearson's R = 0.85 p<0.001 Spatial lag model estimate: 57.86 p<.01 Average building scale Pearson's R = 0.74 p=0.004 Spatial lag model estimate: -0.025 p<.01 Public greenspace Pearson's R = - 0.27 p=0.36 Spatial lag model estimate: 2.079 p<.01 (estimates from spatial lag model - rec by authors)	Geographical features only	Very Low

Author Year	Setting and Design	Measure of neighbourhood design	Primary outcome	Direction of effect for population density	Reported results (95% confidence interval)	Adjusted covariates	Quality (GRADE)
Jin 2020	Chinese neighbourhoods Case/control study 4,329 case neighbourhoods 17,316 control neighbourhoods 4.5km away 'Neighbourhood' not defined	Facilities within 1.5km: Restaurant Shopping Centre Hotel Services (Travel Agent, Ticket Office, Job Centre) Recreational Facilities Public Transit Education Health services	Confirmed Covid-19 case Jan 18 - April 30 2020	NA	<u>Odds Ratios</u> Restaurant: 2.09 (1.95-2 25) Shopping: 2.27 (2.12-2.43) Hotel: 2.32 (2.16-2.48) Services: 1.82 (1.7-1.96) Recreation: (2.27 (2.11-2.43) Public transit: 1.32 (1.23 – 1.41) Education: (1.92 (1.83 – 2.10) Health Service: 4.12 (3.83-4.44) (all higher for cities with population <6million)	<u>All at city level</u> Population size GDP Unemployment Residential mobility	Very Low

↑: Increase in effect with increasing population density**; ↓:** Decrease in effect with increasing population density; **ns**: not significant; **NA:** not applicable

Table 6: Studies of non-COVID-19 respiratory infections in China

Author Year	Setting and Design	Measure of neighbourhood design	Primary outcome	Direction of effect for population density	Reported results (95% confidence interval)	Adjusted covariates	Quality (GRADE)
Liang 2003	Beijing Descriptive study (total population of Beijing in 2003 was 11.8 million)	Population density based on 'urban', 'suburb' and 'far-suburb' categorisation	SARS incidence, mortality, case fatality per million March 2003	↑	<u>Rates at Urban level:</u> Incidence: 3.34/million, Mortality: 0.31/million, Case fatality: 9.2% <u>Rates at Suburb level:</u> Incidence: 2.16/million, Mortality: 0.15/million, Case fatality: 7.0% <u>Rates at Far-suburb level:</u> Incidence: 0.92/million, Mortality: 0.06/million, Case fatality: 6.2%	None	Very low
Xiao 2014	Chansha urban area, Hunan Province, China Case control study Sample size: 1957 cases Control is randomly generated space/time point	Population density (per Ha in 3 bands) At street/township level Public places within 1km: Primary School Middle School Higher Education Places, Hospitals Business District	Confirmed flu H1N1 May 2009- Dec 2010	↑	<u>Odds Ratios</u> <u>Population density:</u> Middle density: Univariate: 6.39 (5.60-7.30) Multivariate: 2.79 (2.39-3.27) High density: Univariate: 8.03 (6.48-9.95) Multivariate: 2.70 (CI 2.11-3.47) <u>Places < 1km:</u> Higher education places Univariate: 10.17 (8.79-11.74) Multivariate: 5.58 (4.6-6.7) Middle school Univariate: 4.71 (4.18-5.31) Multivariate: 1.234 (1.05-1.46)	Geographical features only	Very low

Author Year	Setting and Design	Measure of neighbourhood design	Primary outcome	Direction of effect for population density	Reported results (95% confidence interval)	Adjusted covariates	Quality (GRADE)
Xiao 2014 (cont)		Malls and market			Primary school Univariate: 3.51 (3.10-3.97) Multivariate: 1.417 (1.21-1.67) Hospital Univariate: 4.75 (4.22-5.36) Multivariate: ns not given Business district Univariate: 2.87 (2.45-3.21) Multivariate: ns not given Malls and Market Univariate: 2.63 (2.33-2.97) Multivariate: ns not given		

↑: Increase in effect with increasing population density; **↓:** Decrease in effect with increasing population density; **ns:** not significant

Table 7: Studies in other countries

Author Year	Setting and Design	Measure of neighbourhood design	Primary outcome	Direction of effect for population density	Reported results (95% confidence interval)	Adjusted covariates	Quality (GRADE)
Birenbaum-Carmeli 2020	Israel Ecological study residential communities with population > 5,000, approx. 197 municipalities	Population density (per km^2)	Confirmed cases per 1000 residents Up to 2 June 2020	↑	Regression coefficient Population density: 0.00024 (SE 0.0 β=0.439). An increase of 100 people per km^2 raises morbidity by 2.4 patients per 100,000	Socioeconomic status Population age 65+ Minority status (Jewish or Arab)	Low
Olowokure et al 2003	West Midlands, children <5 yrs. Ecological study census enumeration districts, number of enumeration districts not given, total population of children <5 350,000	Resident population per km^2	Hospital admission with lab confirmed invasive H. influenzae - per 100,000 children <5 yrs. 1990-1992 pre-Hib vaccination 1992-1994 post-Hib vaccination	↓	Relative incidence Population density by sextiles, second lowest to highest, reference group lowest density pre vaccination 1.10 (0.64–1.88) 0.61 (0.34–1.11) 0.69 (0.39–1.22) 0.71 (0.41–1.24) 0.52 (0.30–0.92) p=.0023 post vaccination 0.93 (0.35–2.47) 0.82 (0.30–2.23) 0.49 (0.17–1.46) 0.63 (0.23–1.73) 0.40 (0.14–1.15) p =.028	None	Very low

↑: Increase in effect with increasing population density; **↓:** Decrease in effect with increasing population density; **ns:** not significant; **Hib:** Haemophilus Influenzae type B

DISCUSSION AND CONCLUSIONS

Summary of findings

This is the first systematic review we are aware of that has aimed to assess the associations between population density and neighbourhood design and transmission of Covid-19 and other respiratory infections.

We found that studies reported conflicting findings relating to population and housing density. Overall, the available evidence provides no clear evidence of either a positive or negative association between population or housing density and the transmission of Covid-19 and other respiratory infections.

Several studies investigated other aspects of neighbourhood design including the number of housing units per building or residential scale, walkability, mixed use, proximity to schools and other facilities, and indicators of quality. For each of these, there was only a small number of studies and they reached conflicting findings for most of these characteristics. Overall, no clear conclusion can be drawn about any association between each of these characteristics and transmission of infection.

Limitations of reviewed literature

A major limitation is the overall poor quality of included studies. Most were ecological studies and a few had a small number of units of analysis. Several studies did not control for covariates likely to influence the outcomes, such as age, socio-economic status and co-morbidity, and some presented only bivariate analyses. Some studies focused on characteristics of people with increased susceptibility and included few data on neighbourhood characteristics. On the other hand, studies focusing on features of neighbourhood design often did not control for the characteristics of the people living in different kinds of neighbourhoods. These are susceptible to confounding by these factors as it is highly likely that relevant characteristics of people living in densely populated areas will differ from people living in less densely populated areas. Where socio-economic status was included, different measures were used. Relevant covariates included median income (Credit 2020; Nguyen et al. 2020), insurance status (Cromer et al. 2020), poverty rate (Bryan et al. 2020; Cromer et al. 2020; Nguyen et al. 2020) and various composite measures (DiMaggio et al. 2020; Gu et al. 2020; Birenbaum-Carmeli and Chassida 2020). These may reflect different aspects of socioeconomic status that affect the risk of infection in different ways, which complicates comparison between studies.

Studies varied in the duration and time period of the data studied. Most studies of Covid-19 reported findings early in the pandemic. This brings the potential for bias by the kinds of areas that the virus seeded to first. Some of the Chinese studies included the time of Chinese New Year, when people travel out of cities, so the measure of population density would be misleading. Amenities such as schools and many commercial premises, included in some studies, were closed during Chinese New Year and during lockdown, which would also give misleading results. In both USA and China there were also differences in testing policies between areas and at different time points.

Most of the studies were from the USA or China, so findings may not generalise directly to Scotland. Neighbourhood contexts in these countries differ greatly from each other, and from Scotland. Some studies focused on specific populations like pregnant women or young children, so may not be generalizable to the wider population. We found only one study from the UK, which studied *H. influenzae* in preschool children in the 1990s so is unlikely to be generalisable to other infections in the wider population in the 2020s.

The studies used different proxies for transmission including test positivity, rates of reported cases, hospital admissions and mortality. These may be subject to different biases, particularly for conditions like Covid-19 where a large proportion of cases are asymptomatic and severity is strongly influenced by factors such as age and comorbidity. In settings without free universal healthcare there may be bias by ability to pay if high income people are more able to afford testing and treatment, or if low income people fear losing income if a positive test means they will have to stay off work. These factors may mean that low income people only present for testing if severely ill. Even where testing is free of charge, studies may also be biased by access, especially if testing is only available in hospitals, which in some settings are often found in the densely populated centre of a city. In these settings, healthcare workers and their families, who are a high risk group, may disproportionately live in the densely populated areas near the hospital. This may introduce another source of bias.

The studies used different proxies for 'neighbourhood'. We only included studies at city, subcity or small neighbourhood level but the units had widely varying population sizes. These ranged from 200 households in UK census enumeration districts, in the single UK study (Olowokure et al. 2003) to cities or city districts containing millions of people in some of the Chinese studies (Liu, Yuan, et al. 2020; You, Wu, and Guo 2020). Most USA studies used census tracts (around 4,000 population) or zip codes/zip code tabulation areas (average 8,000 population). Appendix 3 gives further detail of the units of analysis used in the studies. Some studies did not indicate the measure of population density used in the analysis. The studies also used different indicators for aspects of neighbourhood design, which may reflect different concepts. Several studies reported a high correlation between neighbourhood characteristics, making it difficult to disentangle the effects of each. The studies used diverse approaches to analysis and a range of different analysis metrics, and we were unable to synthesise results.

Strengths and Limitations of the present review

We followed established guidelines for systematic reviews (Moher et al. 2009) and took a systematic approach throughout. We constructed and tested a detailed search to identify papers and supplemented this by searching the reference lists of included papers and performing forward citation tracking. Two team members independently screened titles and abstracts and full papers. Similarly, two team members independently extracted data from each study and assessed quality before agreeing on the final data by consensus. A limitation is the lack of a standard tool for ecological studies, which meant we adapted a tool that had been developed for another review (Betran et al. 2015). The review identifies clearly that most published papers on this topic are of very low quality and none are set in a Scottish context. By identifying and critiquing the range of research designs and measures that have been used, the review can help guide higher quality research that would be better able to inform Scottish policy.

Comparison with other literature

There has been an assumption that higher population density would increase transmission, on the understanding that higher density would increase the likelihood of face to face contact (Sharifi and Khavarian-Garmsir 2020; Rocklöv and Sjödin 2020). Notably, some of the studies we found (Vahidy et al. 2020; Gu et al. 2020; Credit 2020) aimed to explore racial differences in Covid-19 and included population density as a covariate on the assumption that it would be a mediator.

It might seem surprising that some studies found that higher population density was associated with lower rates of infection. Several reasons have been suggested in the literature for this. One reason may be that people in denser, more walkable, neighbourhoods are better able to comply with social distancing. Two studies (Hamidi and Zandiatashbar 2021; Chan 2020) have shown greater reduction in journeys during social distancing restrictions among people living in compact areas. The authors of one (Hamidi and Zandiatashbar 2021) speculated that this may reflect better awareness of the severity of the disease, better internet infrastructure allowing greater use of online alternatives, and better pedestrian access to essential shops and services in local areas, allowing people to avoid large stores where more people gather.

Another consideration is that people in less densely populated suburban or rural areas may travel into central areas of the city to access work, retail and other services, encountering a greater number of people outside their area of residence. One of our included studies (Huang et al. 2020) from Hong Kong considered venue density, defined as the number of venues in each area that had been visited by a confirmed case in the previous fortnight. This was intended as a marker of the risk of transmission. They reported that venue density was negatively associated with population density but positively associated with residential, commercial and greenspace densities, each defined as the proportion of the land area used for that purpose. This suggests that factors other than population density may be more important determinants of the number of places that people visit, and therefore the risk of contact with the virus.

Another possible explanation is the effect of living in an environment that encourages physical activity on disease severity. In a Western context, denser urban areas tend to be more walkable than areas of urban sprawl (Sallis et al. 2016; Giles-Corti et al. 2016). Early studies in particular may only identify more serious cases due to restrictions on testing that were in place early in the pandemic. The chronic diseases that are associated with physical inactivity are also associated with higher severity of Covid-19 (Liu, Cui, et al. 2020; Nystoriak and Bhatnagar 2018; Nishiga et al. 2020; Crisafulli and Pagliaro 2020). It is plausible that people living in neighbourhoods that encourage physical activity would be less likely to have severe disease and so less likely to be tested and receive a positive diagnosis. It has also been suggested that physical activity may also have more direct effects on immunity (Nieman and Wentz 2019) and therefore reduce susceptibility to Covid-19. A UK study found that objectively measured physical activity reduced the odds of Covid-19 outcomes (Zhang et al. 2020). Importantly, the association between urban density and physical activity may not apply in the same way in a Chinese context (Sun, Lai, et al. 2020; Lu, Xiao, and Ye 2017). China was the setting for several of the papers included in our review that found a positive association between population density and transmission. This highlights the importance of understanding contextual differences when interpreting these findings.

Other authors have observed the lack of clear relationship with population density and argue that other factors are more important, such as poverty, front line employment, patterns of commuting and household overcrowding (Kang et al. 2020; Hamidi, Ewing, and Sabouri 2020). These may have complex associations with population density and other neighbourhood characteristics, and there are clearer pathways through which these factors can increase transmission of respiratory infections.

Several authors have suggested features of housing design that may reduce transmission. These include low rise building forms (Megahed and Ghoneim 2020), provision of space to reduce overcrowding and facilitate home working (Fezi 2020; Kang et al. 2020; Megahed and Ghoneim 2020), and specific internal features such as ventilation (Fezi 2020; Pinheiro and Luís 2020), and touchless contact points (Pinheiro and Luís 2020; Megahed and Ghoneim 2020). We did not include studies of building materials in our study but did look for studies relating to housing form. We found limited evidence on this. The USA studies of Covid-19 found either no association or a negative association with the number of units per building but the USA study of respiratory infections in children found a positive association with attached homes and mobile homes. The two studies from China of residential building scale or height reached conflicting findings. Taken together, the findings suggest that socioeconomic status is likely to be a more important factor than housing type.

Implications for policy

This study found no consistent evidence of a link between population density and transmission of Covid-19 and other respiratory infections and does not suggest a need to change the current Scottish Government policy of support for 20-minute neighbourhoods. We also found no clear evidence of a link with other aspects of neighbourhood design.

Although our study did not find strong evidence of associations between neighbourhood design and transmission of respiratory infections, there are other, better established, links between compact city form and health determinants including physical activity and mental wellbeing. This suggests that the '20-minute neighbourhood' concept should be positive for health overall. However as the rapid scoping assessment identified (Douglas and Beautyman 2020), optimal infrastructure, services and quality are needed to create the high quality places likely to realise these health benefits.

Planning policy may still be important to reduce transmission, by facilitating physical distancing (Megahed and Ghoneim 2020; Sharifi and Khavarian-Garmsir 2020; Capolongo S 2020). This may include policies that help to reduce the need to travel into crowded city centres and support decentralisation of services and employment such as providing local working hubs. Outdoor spaces can also be designed to allow physical distancing.

The evidence does not indicate a preferred housing form to reduce transmission, but planning policy relating to housing is also important. Household overcrowding is an established risk factor for Covid-

19 and other infections (Barker 2020; Centre for Ageing Better 2020). We did not aim to study household size or overcrowding in the review but several of the studies of Covid-19 in our review included household size (Emeruwa et al. 2020; Cromer et al. 2020; Nguyen et al. 2020) or crowding (Emeruwa et al. 2020; Bryan et al. 2020; Credit 2020; Cromer et al. 2020) as covariates. They all reported a positive association. The provision of more affordable homes, with house sizes and types designed to meet the needs of the population, may help to reduce overcrowding and so prevent transmission in the household setting. Housing that provides space for home working and access to outdoor space may also support physical distancing (Fezi 2020; Kang et al. 2020; Megahed and Ghoneim 2020).

Implications for further research

The small number of studies and overall low quality of available research in this area suggests a need for further research. Studies should be at an appropriate spatial scale to investigate the association between transmission of Covid-19 and population density and other design features at a neighbourhood level. We found no studies from the UK that investigated neighbourhood level associations. Associations may differ significantly between different contexts, and Scottish or UK research is needed urgently to inform Scottish policy.

Associations between different aspects of neighbourhood design and transmission may be complex. It is important to articulate clearly the pathways through which associations are hypothesised to occur and ensure that analyses are well designed to test these. Standardised indicators are needed to measure relevant neighbourhood characteristics to allow comparison between studies.

Transmission of Covid-19 and other respiratory infections is affected by characteristics of the people who live in different kinds of neighbourhood, as well as their spatial features. These include age, race, socioeconomic status, comorbidity, occupational risks, travel behaviours, and others. Household overcrowding, household composition and other household characteristics may be additional influences. It is important to ensure studies measure and control adequately for all these factors in the analyses to avoid spurious findings. Doing so will require a multi-disciplinary approach that uses sophisticated designs and combines different areas of expertise to understand both people and place.

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Appendix 1: Database searches

How is transmission of respiratory viruses, including Covid-19, affected by population density and other features of neighbourhood design?

Database searches

ASSIA (ProQuest)
Timespan: 1987 to present
Date of search: 20201012
Number of results: 11
Search history:
noft(((high OR low) NEAR/2 density NEAR/2 (housing OR dwelling OR population)) OR "population density" OR "dwelling density" OR "development density" OR "compact development" OR "activity density" OR "activity centering" OR "activity centring" OR "street connectivity" OR "housing density" OR "residential density" OR "over-crowding" OR "household composition" OR "20 minute neighbo*" OR "15 minute neighbo*" OR "mixed use neighbo*" OR "environment design" OR "new urbanism" OR "Built Environment" OR "urban design" OR "City Planning" OR ((rural OR urban OR cities OR city) NEAR/10 incidence)) AND noft(influenza OR pneumonia OR rhinovirus OR "Respiratory virus*" OR "acute respiratory infection*" OR "acute respiratory tract infection*" OR influenza OR "Middle East Respiratory Syndrome" OR MERS OR "Severe Acute Respiratory Syndrome" OR SARS OR 2019nCoV OR Betacoronavirus* OR "Corona Virus*" OR Coronavirus* OR Coronovirus* OR CoV OR CoV2 OR COVID OR COVID-19 OR COVID-19 OR HCoV-19 OR nCoV OR "SARS CoV 2" OR SARS2 OR SARSCoV OR SARS-CoV OR SARS-CoV-2)

Avery Index to Architectural Periodicals (EBSCO)
Timespan: inception to present
Date of search: 20201012
Number of results: 30
Search:
TX (((high or low) N2 density N2 (housing or dwelling or population)) or "population density" or "dwelling density" or "development density" or "compact development" or "activity density" or "activity centering" or "activity centring" or "street connectivity" or "housing density" or "residential density" or "over-crowding" or "household composition" or "20 minute neighbo*" or "15 minute neighbo*" or "mixed use neighbo*" or "environment design" or "new urbanism" or "Built Environment" or "urban design" or "City Planning" or ((rural OR urban OR cities OR city) N10 incidence))) AND TX (influenza or pneumonia or rhinovirus or "Respiratory virus*" or "acute respiratory infection*" or "acute respiratory tract infection*" or influenza or "Middle East Respiratory Syndrome" or MERS or "Severe Acute Respiratory Syndrome" or SARS or 2019nCoV or Betacoronavirus* or "Corona Virus*" or Coronavirus* or Coronovirus* or CoV or CoV2 or COVID or COVID-19 or COVID-19 or HCoV-19 or nCoV or "SARS CoV 2" or SARS2 or SARSCoV or SARS-CoV or SARS-CoV-2)

CNKI
Date of search 20201015
Number of results: 306
Limits: Chinese language, journal article

(SU=大流行 OR SU=呼吸道传染病 OR SU=呼吸系统传染性疾病 OR SU=呼吸道传染性疾病 OR SU=呼吸系统传染病 OR SU=H1N1 OR SU=H7N9 OR SU=甲型流感 OR SU=SARS OR SU=新冠 OR SU=严重急性呼吸综合征 OR SU=传染性非典型肺炎 OR SU=新型冠状病毒肺炎 OR SU=中东呼吸综合征 OR SU=MERS OR SU=冠状病毒 OR SU=急性呼吸道疾病 OR SU=鼻病毒)
AND
(SU=人口密度 OR SU=建筑密度 OR SU=城市规划 OR SU=建筑高度 OR SU=城市更新 OR SU=城市公共空间 OR SU=住宅区规划 OR SU=规划设计 OR SU=城市建设规划 OR SU=城市分区规划 OR SU=街道 OR SU=空间 SU=居住密度 OR SU=公共活动空间 OR SU=居住区公共空间 OR SU=混合社区 OR SU=高层住宅小区 OR SU=社区 OR SU=环境设计 OR SU=建设环境)
AND
(SU=流行病学 OR SU=描述流行病学 OR SU=环境流行病学 OR SU=地理流行病学 OR SU=患病率 OR SU=观察性研究 OR SU=生态学研究 OR SU=发病率 OR SU=感染率 OR SU=病死率 OR SU=治愈率)

Embase (Ovid) <1980 to 2020 Week 41>
Date of search: 20201012
Number of results: 326
Search:
----
1 Population Density/ or population density.mp. (29682)
2 ((high or low) adj2 density adj2 (housing or dwelling or population)).mp. [mp=title, abstract, heading word, drug
trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword, floating subheading word, candidate term word] (1816)
3 dwelling density.mp. (44)
4 development density.mp. (19)
5 compact development.mp. (17)
6 activity density.mp. (149)
7 (activity centering or activity centring).mp. [mp=title, abstract, heading word, drug trade name, original title,
device manufacturer, drug manufacturer, device trade name, keyword, floating subheading word, candidate term word] (5)
8 street connectivity.mp. (278)
9 housing density.mp. (202)
10 residential density.mp. (300)
11 over-crowding.mp. (131)
12 household composition.mp. (519)
13 20 minute neighbo?rhood*.mp. (0)
14 15 minute neighbo?rhood*.mp. (0)
15 "mixed use neighbo?rhood*".mp. (9)

16 environment design.mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer,
drug manufacturer, device trade name, keyword, floating subheading word, candidate term word] (474)
17 exp environmental planning/ (13822)
18 new urbanism.mp. (14)
19 Built Environment/ (686)
20 urban design.mp. (494)
21 City Planning/ (2372)
22 (rural population/ or urban population/ or city/) and incidence/ (4405)
23 or/1-22 (51747)
24 exp Coronavirinae/ (19655)
25 exp Coronavirus infection/ (21166)
26 (Betacoronavirus* or Corona Virus* or Coronavirus* or Coronovirus* or CoV or CoV2 or COVID or COVID-19 or COVID-19
or HCoV-19 or nCoV or SARS CoV 2 or SARS2 or SARSCoV or SARS-CoV or SARS-CoV-2 or 2019nCoV).mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword, floating subheading word, candidate term word] (78598)
27 24 or 25 or 26 (85523)
28 23 and 27 (326)

Ovid MEDLINE(R) and In-Process & Other Non-Indexed Citations <1946 to October 09, 2020>
Date of export: 20201012
Results: 773
Search:
----
1 (Longitudinal analyses of the relationship between development density and the COVID-19 morbidity and mortality
rates: Early evidence from 1,165 metropolitan counties in the United States).m_titl. (1)
2 Does Density Aggravate the COVID-19 Pandemic?.m_titl. (0)
3 Population Density/ or population density.mp. (30854)
4 Residence Characteristics/ (33999)
5 ((high or low) adj2 density adj2 (housing or dwelling or population)).mp. [mp=title, abstract, original title,
name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]
(1786)
6 dwelling density.mp. (32)
7 development density.mp. (18)
8 compact development.mp. (22)
9 activity density.mp. (185)
10 (activity centering or activity centring).mp. [mp=title, abstract, original title, name of substance word,
subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms] (5)
11 street connectivity.mp. (249)
12 housing density.mp. (183)

13 residential density.mp. (276)
14 over-crowding.mp. (97)
15 household composition.mp. (527)
16 20 minute neighbo?rhood*.mp. (0)
17 15 minute neighbo?rhood*.mp. (0)
18 "mixed use neighbo?rhood*".mp. (14)
19 environment design.mp. [mp=title, abstract, original title, name of substance word, subject heading word,
floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms] (6543)
20 Environment Design/ (6423)
21 new urbanism.mp. (8)
22 Built Environment/ (540)
23 urban design.mp. (428)
24 City Planning/ (2234)
25 (rural population/ or urban population/ or cities/) and incidence/ (6087)
26 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17 or 18 or 19 or 20 or 21 or 22 or
23 or 24 or 25 (78618)
27 exp Coronavirus/ or exp Coronavirus Infections/ or exp Rhinovirus/ or exp Influenza, Human/ or exp Pneumonia,
Viral/ or exp Respiratory Syncytial Viruses/ or exp Respiratory Syncytial Virus Infections/ (108699)
28 (Respiratory virus* or acute respiratory infection* or acute respiratory tract infection* or influenza or Middle
East Respiratory Syndrome or MERS or Severe Acute Respiratory Syndrome or SARS or 2019nCoV or Betacoronavirus* or Corona
Virus* or Coronavirus* or Coronovirus* or CoV or CoV2 or COVID or COVID-19 or COVID-19 or HCoV-19 or nCoV or SARS CoV 2 or SARS2 or SARSCoV or SARS-CoV or SARS-CoV-2).mp. (192236)
29 27 or 28 (209375)
30 26 and 29 (773)

Scopus

Date of search 20201012
Timespan: All years.
Number of results: 671
Search history:
TITLE-ABS-KEY ((((high OR low) W/2 density W/2 (housing OR dwelling OR population)) OR "population density" OR "dwelling density" OR "development density" OR "compact development" OR "activity density" OR "activity centering" OR "activity centring" OR "street connectivity" OR "housing density" OR "residential density" OR "over-crowding" OR "household composition" OR "20 minute neighbo*" OR "15 minute neighbo*" OR "mixed use neighbo*" OR "environment design" OR "new urbanism" OR "Built Environment" OR "urban design" OR "City Planning") AND (influenza OR pneumonia OR rhinovirus OR "Respiratory virus*" OR "acute respiratory infection*" OR "acute respiratory tract infection*" OR influenza OR "Middle East Respiratory Syndrome" OR mers OR "Severe Acute Respiratory Syndrome" OR sars OR 2019ncov OR betacoronavirus* OR "Corona Virus*" OR coronavirus* OR coronovirus* OR cov OR cov2 OR covid OR Covid-19 OR covid-19 OR hcov-19 OR ncov OR "SARS CoV 2" OR sars2 OR sarscov OR sars-cov OR sars-cov-2) AND (epidemiolog* or transmission or incidence or prevalence or outbreak* or morbidity or mortality))

Wanfang
Date of search 20201015
Number of results: 73
Limits: Chinese language, journal article
(主题:(大流行)+主题:(呼吸道传染病)+主题:(流感) +主题:(传染性) +主题:(空气传播)+主题:(covid)+主题:(H1N1)+主题:(H7N9)+主题:(SARS)+主题:(新冠)+主题:(严重急性呼吸综合征）主题:(传染性非典型肺炎）+主题:(新型冠状病毒肺炎) +主题:(中东呼吸综合征）+主题:(MERS) +主题:(冠状病毒）+主题:(急性呼吸道疾病) +主题:(鼻病毒)）
AND
（主题:(人口密度)+主题:(建筑密度)+主题:(城市更新)+主题:(城市规划)+主题:(街道)+主题:(建筑高度)+主题:(城市公共空间)+主题:(住宅区规划)+主题:(规划设计)+主题:(城市建设规划)+主题:(城市分区规划) +主题:(居住密度)+主题:(公共活动空间)+主题:(居住区公共空间)+主题:(环境设计)+主题:(混合社区)+主题:(高层住宅小区) +主题:(建设环境)）
AND
(主题:(死亡率)+主题:(患病率)+主题:(观察性研究)+主题:(生态学研究)+主题:(发病率)+主题:(感染率)+主题:(病死率)+主题:(治愈率)+主题:(流行病学)）
NOT
（主题:(气象)+主题:(非传染性疾病）+主题:(慢性病）+主题:(肠）+主题:(癌）+主题:(学校)+主题:(血清)+主题:(疫苗)+主题:(糖尿病)+主题:(手足口)+主题:(性传播)+主题:(痢疾)+主题:(艾滋病)+主题:(性病)+主题:(登革热)+主题:(腹泻)+主题:(疟疾)+主题:(高血压)+主题:(精神)+主题:(梅毒)+主题:(虫)+主题:(肝炎)+主题:(血管)+主题:(淋病)+主题:(龋)+主题:(肥胖)+主题:(伤害)+主题:(骨)+主题:（分子)+主题:(食源)+主题:(肿瘤)）

Web of Science
Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC
Date of export: 20201012
Timespan: All years.
Number of results: 553
Search history:
TS=(((high or low) NEAR/2 density NEAR/2 (housing or dwelling or population)
) or "population density" or "dwelling density" or "development density" or "compact development" or "activity density" or "activity centering" or "activity centring" or "street connectivity" or "housing density" or "residential density" or "over-crowding" or "household composition" or "20 minute neighbo*" or "15 minute neighbo*" or "mixed use neighbo*" or "environment design" or "new urbanism" or "Built Environment" or "urban design" or "City Planning" or ((rural or urban or cities or city) NEAR/10 incidence)) AND TS=(influenza or pneumonia or rhinovirus or "Respiratory virus*" or "acute respiratory infection*" or "acute respiratory tract infection*" or influenza or "Middle East Respiratory Syndrome" or MERS or "Severe Acute Respiratory Syndrome" or SARS or 2019nCoV or Betacoronavirus* or "Corona Virus*" or Coronavirus* or Coronovirus* or CoV or CoV2 or COVID or COVID-19 or COVID-19 or HCoV-19 or nCoV or "SARS CoV 2" or SARS2 or SARSCoV or SARS-CoV or SARS-CoV-2)

Appendix 2: Glossary of neighbourhood and other terms

General Terms

Location / Setting	This refers to the study area, and may be a country, region or city. Each setting has different characteristics, including population density, housing and neighbourhood design, special policies for COVID-19, developed and under-developed areas, etc.
Population	This refers to the people within the study area. Sub-group information may include income level, ethnicity, gender, SES.
Time Period	For our purposes, the time period refers to the period that was covered by the study (including any information about the phase of the epidemic at that time, if known).

Density Terms

Population density	Population density refers to the number of people in a given area. The ONS (2019) measures population density as the number of people resident per square kilometre. As measures of population density, studies use population census-derived estimates and geographic boundaries. Sometimes as a proxy, studies may ask people to report the number of low- or high-rise buildings in their neighbourhood and estimate population density by the number of units of different buildings.
Housing / Dwelling density	Dwelling density refers to the number of dwellings in a given area, often measured as dwellings per Hectare.

Housing and Neighbourhood Design Terms

Neighbourhood	The concept of neighbourhoods is central to planning policy, but does not have a single, clear definition. (A useful overview of the literature is available in Allen (2018).) Neighbourhoods tend to be sub-areas of a city (or suburban or rural district) with a discrete identity. In the papers we study, the concept of a "neighbourhood" may refer to an area that is externally defined as such (for example, in planning policies or as voting districts) or which is defined by something less tangible, such as a sense of community.
Neighbourhood design / characteristics	Neighbourhood design refers to the components of a particular neighbourhood (for example, housing, green spaces, streets and roads, employment opportunities, amenities etc) and how those components relate to each other (for example, housing density; whether shops and green spaces are accessible by foot/public transport; etc). Neighbourhoods may have a single or dominant purpose (residential, commercial, etc) or may be designed to meet all or most of a person's everyday needs close to home (this is where the concept of 15-/20-minute neighbourhoods, or mixed-use neighbourhoods, comes in). Neighbourhood characteristics may also refer to descriptions of the neighbourhood as a whole, such as location (city centre, peri-urban); age (modern, new, old neighbourhoods); SES (slum, middle-class neighbourhood, etc).

Housing design / characteristics	Housing design may refer to the way an individual house, or a type of housing, is designed. This may include features such as size, accessibility. It may also refer to how housing is organised (e.g. detached houses, terraced houses, low-rises, high-rises, etc). In our study we are not considering internal layout, like number of rooms or open plan layout, or aesthetic features and building materials.

References

Allen, N (2018) "Concepts of Neighbourhood: A Review of the Literature" Building Better Homes Towns and Cities: National Science Challenge Working Paper 18-02 [Online] Available at: https://www.buildingbetter.nz/publications/urban_wellbeing/Allen_2018_Concepts_of_Neigbourhoods_WP18-02.pdf

ONS [Office of National Statistics] (2020) "Population Estimates for the UK, England and Wales, Scotland and Northern Ireland, provisional: mid-2019" [Online] Available at: https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/bulletins/annualmidyearpopulationestimates/mid2019

Other Glossaries:

Glossary of Housing Terms (Royal Borough of Kensington & Chelsea): https://www.rbkc.gov.uk/sites/default/files/atoms/files/Glossary%20of%20housing%20terms.pdf#:~:text=Glossary%20of%20Housing%20terms%20Affordable%20housing%20Affordable%20housing,will%20also%20include%20starter%20homes.%20Affordable%20rented%20housing

Glossary of Housing Terms Used by Councils (London Borough of Hammersmith & Fulham): https://www.lbhf.gov.uk/sites/default/files/section_attachments/glossary_housing_terms_3.1_tcm21-108364.pdf

Glossary of Planning Terms (Planning Portal): https://www.planningportal.co.uk/directory/4/glossary/category/7

Appendix 3: Units of analysis used in reviewed papers

Unit of analysis	Papers using this unit	Purpose of unit	Population size
UK census enumeration district	Olowokure	Small areas originally defined to manage workload of census enumerators, commonly used for small area census outputs. Defined for censuses up to 1991 but now superseded.	Each enumeration district contains 200 households, approximately 400 people
US census tracts	Bryan Cromer Gu Joseph	Created for tabulation and presentation of small area census data.	Range 1.200 to 8,000 people – average 4,000.
US zip codes	Nguyen NYC Furman Centre	Created to define delivery routes for the US postal service	Average population size 8,000 but can vary up to maximum 114,000
US zip code tabulation areas	Credit DiMaggio Vahidy	Developed from zip codes to create an areal feature dataset.	In most cases the ZTCA is the same as the zip code, so population size similar, but excludes unpopulated zip codes.
Street/township in Chansha urban area	Xiao	Unclear, subdistrict level communities	Average population size 12,500
New York City Neighbourhood Tabulation Area	Emeruwa	Developed to enable small area population projections in New York City. Aggregated from census tracts.	*Minimum* 15,000 residents.
Hong Kong Tertiary Planning Unit	Huang	Administrative units also used for census	Average population 25,000
Israeli municipalities	Birenbaum-Carmeli	Administrative unit	Minimum 5,000 people, average 45,700
Wuhan Districts	You	Administrative divisions of the city	Population ranges from 370,000 to 1,350,000

Cities in Hubei province	Liu	City and surroundings	Population size ranges from 76,000 to 9.7 million

Sources:

Most population sizes derived from included papers. Additional sources:

US Census Bureau (2018) Census Tracts for the 2020 Census-Final Criteria https://www.federalregister.gov/documents/2018/11/13/2018-24567/census-tracts-for-the-2020-census-final-criteria

US Census Bureau (2020) ZIP Code Tabulation Areas (ZCTAs) https://www.census.gov/programs-surveys/geography/guidance/geo-areas/zctas.html

NYC Department of Planning (undated) Neighborhood Tabulation Areas (Formerly "Neighborhood Projection Areas") https://www1.nyc.gov/site/planning/data-maps/open-data/dwn-nynta.page#:~:text=Archived%20Data%20Sets-,Neighborhood%20Tabulation%20Areas%20(Formerly%20%22Neighborhood%20Projection%20Areas%22),plan%20for%20New%20York%20City.

Office of Population Censuses and Surveys (1992) 1991 Census Definitions Great Britain. London: HMSO. https://census.ukdataservice.ac.uk/media/51162/1991_defs.pdf