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Compact cities and the Covid-19 pandemic: 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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ABSTRACT

Living in compact neighbourhoods that are walkable, well connected, with accessible green space can benefit physical and mental health. However, the pandemic raises concern up to what extent features of compact neighbourhood design affect transmission of viral respiratory infections. We conducted a systematic review to identify, appraise and synthesise evidence reporting associations between transmission of respiratory viruses, including Covid-19, and dwelling or population density or other features of neighbourhood design. Twenty-one studies met our inclusion criteria. These studies used different measures of neighbourhood design, contributing to inconsistent findings. Whereas no convincing conclusion can be drawn here, the outcome of this review indicates that robust, global evidence is warranted to inform future policies and legislation concerned with compact neighbourhood design and transmission of respiratory and viral infection.

1. Introduction

Urban planning originated in the late nineteenth century as a way to improve population health by improving in built environments (e.g., sanitation, lighting and ventilation) to combat outbreaks of infectious disease (Corburn, 2012). In recent decades, new challenges have arisen, as car-dominated urban developments and physically inactive lifestyles contribute to the increasing prevalence of non-communicable diseases (NCDs) (Sallis et al., 2016). As the population ages, these NCDs become increasingly important. They include obesity, cardiovascular disease, diabetes and stroke causing more than 15 premature deaths per year worldwide. (World Health Organization, 2021c). Urban neighbourhoods can influence multiple health determinants such as physical activity (Adkins et al., 2017; Saelens et al., 2003) and mental health (Ige-Elegbede et al., 2020). Over the past two decades, there has been growing understanding of the multiple dimensions through which neighbourhood environments may impact population health and well-being, including the mix of people, their lifestyles, community, local economy, activities, built environment, natural environment and global ecosystem (Barton and Grant, 2006; Giles-Corti et al., 2016).

The Covid-19 pandemic has caused significant social and economic disruption and continues to cause morbidity and mortality around the world (World Health Organization, 2021a). Policy responses to the pandemic have included restrictions on mobility, changing how people interact with each other and with their environment. The pandemic, and responses to control it, may bring new implications for urban design. This includes consideration of whether, and how, neighbourhood environments might affect disease transmission, and also how the built environment might mitigate the impact on health of people being asked to stay home, reduce their social interactions and restrict travel (Kang et al., 2022). A better understanding of these factors can allow these to be taken into account in the future policy and design practice to control transmission of viral respiratory viruses.

1.1. Compact cities and health

Almost 50 years ago, based on an ideal of medieval cities, the 'compact city' concept was put forward to increase environmental

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sustainability, reduce urban sprawl and protect the countryside (Dantzig & Saaty, 1973). The early concept proposed that 250,000 people could live in a two-mile neighbourhood with eight-story towers. This would create high residential density in a self-sufficient area with a clear boundary, so that the micro-climate, energy consumption and travel distances could be controlled. Subsequently, the concept was expanded to include centralised activity and intensive land use to reduce commuting time, car use and greenhouse gas emissions and alleviate resource shortages (Mouratidis, 2018). During that time, low-density urban forms were considered more liveable which to a perceived conflict between 'sustainability' and 'liveability'.

Around the year 2000, the 'compact city' was redefined to combine sustainability and liveability (Burton, 2000). A compact city is defined as "… intensification of the use of space within the city through higher residential densities and centralization, mixed land uses, limits on development beyond the periphery of the city and efficient public transport and dimensions encouraging walking and cycling behaviours, which may be achieved by an increase in population density, intensive use of buildings, re-use of brownfield and conversion of existing development." (Wang, 2022, p.24). This has been operationalised in the recent concept of 15-min neighbourhoods in Paris and Shanghai, or 20-min neighbourhoods in Melbourne and Scotland (Tomorrow City, 2020; Shanghai Government, 2016; Victoria State Government, 2018; Scottish Government, 2020). This is an urban design that creates neighbourhoods in which shops, services and amenities are located in local centres so that residents can meet their daily needs within a 15 min or a 20 min walk from their home. This requires sufficient density of resident population in each neighbourhood to sustain these services. Nowadays, the concept has been further expanded to include high quality green and open spaces, affordable homes and high quality of services and amenities to create a walkable, green and sustainable city (Wang, 2022).

The 'compact city' provides a good example of potential links between neighbourhood design and health. Unsurprisingly, given the focus on walkability, much of the research on compact cities and health focuses on physical activity. A multi-country study of adults in 14 cities found increased physical activity was associated with living in neighbourhoods with higher net residential, intersection, public transport and park density but not mixed land use or distance to nearest public transport (Sallis et al., 2016). A modelling study of six cities (Melbourne, Sao Paolo, Delhi, London, Boston, Copenhagen) predicted reductions in the prevalence of cardiovascular disease, respiratory disease and diabetes would result from a reduction in physical inactivity and reduced vehicle emissions in a more compact urban form (Stevenson et al., 2016). Compact city designs may also bring mental health benefits. Local public space and community venues will facilitate informal and formal social interaction, which benefits mental health (Evans, 2003). Compact design that includes accessible, high quality urban green space should also benefit health as there is strong evidence of benefits to physical and psychological wellbeing from exposure to green spaces (Kang et al., 2022; Lai et al., 2020).

1.2. Compact cities in a pandemic

The Covid-19 pandemic brings new issues for policy, practice and research. An important consideration is whether, and how, neighbourhood design might impact the transmission of communicable diseases. Covid-19 is caused by the SARS CoV2 virus, which is spread by respiratory particles in aerosols and droplets (World Health Organization, 2021b). It spreads most easily between people in close face to face contact or in crowded, poorly ventilated indoor settings. The risk of transmission in outdoor settings is much lower, but outdoor transmission can occur, particularly in crowded outdoor gatherings where people are not wearing masks (Bulfone, 2021).

Ironically, the same neighbourhood characteristics that are beneficial for non-communicable diseases may be harmful to communicable disease control. There have been concerns that the higher population and dwelling densities in compact designs might facilitate transmission of SARS CoV2 by increasing indoor and outdoor crowding and levels of face to face interaction (Sharifi & Khavarian-Garmsir, 2020). On the other hand, a recent study indicates a protective effect of objectively measured physical activity on Covid-19 transmission (Zhang et al., 2020). This suggests that a compact city that encourages physical activity could help to reduce transmission.

1.3. Review aims

We carried out a systematic review to address the research question: How is transmission of viral respiratory viruses, including Covid-19, affected by population density and other features of compact neighbourhood design? Based on the definition of the compact city, the neighbourhood characteristics in our study included dwelling or population density, housing type, street connectivity or walkability, land use mix and other features of '15-/20- minute neighbourhoods'. We restricted our review to studies that consider these characteristics at the neighbourhood, sub-city, or city level. The detailed protocol for this systematic review, published on Prospero on October 14, 2020 (ID: CRD42020212949), was developed in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA) (Moher et al., 2009).

2. Methods

2.1. Search strategy

We searched Medline, Embase, Web of Science, Scopus, ASSIA, Avery Index to Architectural Periodicals, Wanfang and CNKI from inception to October 2020 using comprehensive search strategies (Appendix 1). As many studies were conducted in China, we used English and Chinese databases. Studies in the Chinese language were screened by the two Chinese reviewers in our group (XZ and ZS). Colleagues with relevant language skills screened studies in languages other than English and Chinese. Based on predefined eligibility criteria, two reviewers independently screened the titles and abstracts with a third reviewer screening the conflicts. Full text papers were then reviewed independently by two reviewers, and any discrepancies discussed and agreed in a team meeting. Finally, we manually checked the reference lists of included papers and performed forward citation checking for additional relevant studies.

2.2. Eligibility criteria

Eligible studies reported quantitative empirical analyses investigating associations between neighbourhood characteristics at neighbourhood, sub-city, or city level and viral respiratory infectious diseases incidence, prevalence, test positivity, hospital admission, or mortality. Studies excluded from this review were: 1) non-human studies; 2) studies of non-respiratory or non-viral diseases; 3) studies about overcrowding in-home or household composition; 4) studies concerned with building materials, air and water quality; 5) studies on the design of healthcare, education or transport systems; 6) studies assessing social mobility or effects of social distancing; 7) studies with no measure of transmission; 8) modelling studies; 9) studies not in a high- or middle-income country (see Table 1). We excluded studies from low-income countries because the urban context is likely to differ between high- and low-income countries which is likely to affect the association with transmission.

2.3. Data extraction and management

For each eligible study, we extracted data on details of the study (i.e., first author, year of publication, study design, country, the period

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 Housing type Street connectivity or walkability Land use mix Features of 'smart urbanism' or '15-/20- minute neighbourhoods'	Overcrowding in home or household composition (bedroom number, number of adults) Studies concerned with building materials, air and water quality 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

studied), neighbourhood (i.e., neighbourhood setting, measures of neighbourhood environment), respiratory infectious disease (i.e., infectious agents type, outcome measured) and main findings (i.e., analysis metric, effect size, covariates included in the analysis). Data were extracted by two investigators independently and any discrepancies agreed by consensus.

2.4. Data synthesis

Due to heterogeneity, predominantly in exposure and/or outcome characteristics, we conducted narrative analyses. We summarised and compared the neighbourhood and viral respiratory infectious diseases characteristics of each eligible study. Subsequently, we compared the above-mentioned characteristics after categorizing the studies into subgroups based on countries, type of infectious diseases and different measures of a neighbourhood.

2.5. Quality and risk of bias assessment

Two team members appraised each study, with discrepancies in views resolved by consensus. We applied the CASP checklists for cohort and case/control studies. For ecological studies, we adapted a checklist originally from another review (Betran et al., 2015). The checklist consisted of 14 items which included items regarding study design, statistical analysis methods and quality of reporting (Table S1). We graded study quality using the Grades of Recommendation, Assessment, Development and Evaluation (GRADE) system (Guyatt et al., 2008). To do this, we used the approach recommended by Usher Network for Covid-19 Evidence Reviews (UNCOVER): observational studies are given an initial grading of low, then upgraded if multiple studies show consistent results or downgraded if quality appraisal identified the potential for bias in the findings.

3. Results

3.1. Study selection

The database searches identified a total of 2743 articles. After removing duplicates and including articles detected from citation tracking, 1890 articles were screened. A total of 21 articles were eligible for inclusion in the systematic review (Fig. 1). The retained studies were based in the USA (13), China (6), Israel (1) and UK (1) covering Covid-19 (15), influenza (1), SARS (1), lower respiratory infections in children (1), and Haemophilus influenzae in children (1). The Covid-19 studies were all in the first wave of the pandemic, before vaccines were available, when countries were introducing rapidly changing social distancing measures. They considered neighbourhood design features including population density, housing units per building, scale and type, walkability, active commuting, land use mix, school density/proximity, other facilities density/proximity.

3.2. Population density

Population density was the feature of a compact city that was most studied in our included papers, being included in 20 of the 21 studies. Of the studies of Covid-19, eight found a positive association with population density, six a negative association and one found no association. However, several of these were not statistically significant or small effects and the quality of the studies was generally low, often with no adjustment for characteristics of the population that would affect the

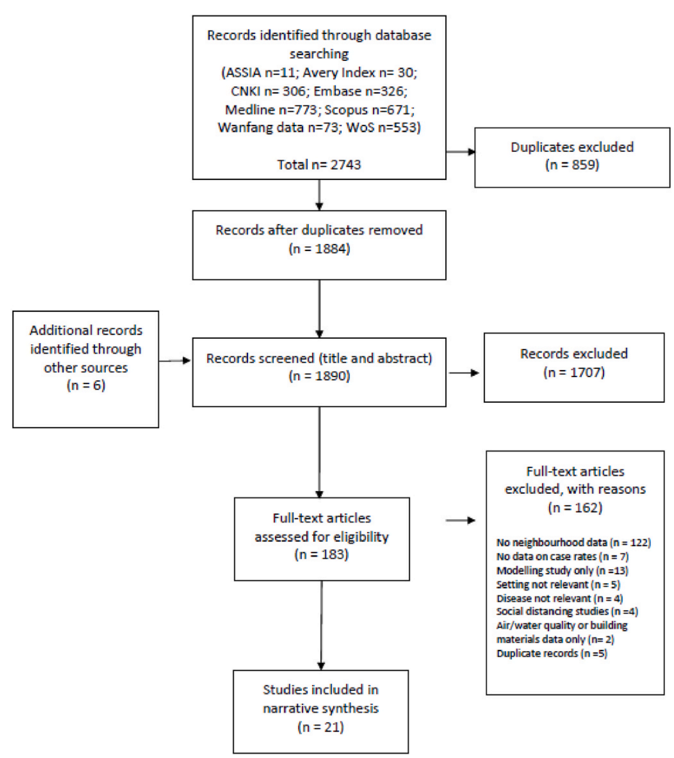

Fig. 1. PRISMA flow diagram of study selection

Table 2
Studies in USA

Author Year	Setting	Measure of neighbourhood design	Primary outcome	Direction of effect for population density	Effect estimates (95% confidence interval)	Adjusted covariates	Quality (GRADE)
Bryan 2020	Chicago: 795 census tracts	Population density (per mile^2) % units in buildings with 20+ units	Mortality rate – deaths recorded as caused by Covid19 Mar 16th to Jul 22nd' 2020	↓ ns	Rate ratio Population density: 1 (0.0–1.0) % units in buildings with 20+ units: 1 (0.997–1.00)	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 All at census tract level	Low
Credit 2020	Chicago: 54 zip codes New York: 177 zip codes	Population density (per m^2) Percent pedestrian and bike commuters Hospital accessibility Percent food desert tracts	Confirmed Covid-19 cases per head up to 1st May 2020	↓ ns	Correlation coefficient Chicago Population density: 26.6 (13.9) p = .06 Active commuting: 0.47 (0.41) p = .28 New York Population density: 1.06 (1.37) p = .4 Active commuting: 0.56 (0.29) p = .05	Age Race Occupation in Healthcare Overcrowding Median Income Testing rate	Low
DiMaggio 2020	New York: 177 zip code tabulation areas	Population density Housing density School density All (per mile^2)	Positive SARS CoV 2 tests per 10,000 and proportion of tests positive up to 22nd April 2020	↑ ns	Incidence density ratio Housing density: 1.08 (0.65–1.78) Population density ns in model, not reported	>65 yrs. Black/African American COPD Heart disease	Low
Nguyen 2020	US states: 7625 zip codes	Definition of population density not stated Indicators of: • Walkability • Urban development • Physical disorder	Covid-19 cases per 100,000 up to 21st June 2020	↑	Rate Ratio Population density: varies by model, range 1.01–1.04 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: zip codes	Population density (per mile^2) Housing ≥10 units	Zip code quintiles based on number of Covid-19 cases per 1000 people on 8th 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

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Table 2 (*continued*)

Author Year	Setting	Measure of neighbourhood design	Primary outcome	Direction of effect for population density	Effect estimates (95% confidence interval)	Adjusted covariates	Quality (GRADE)
Cromer 2020	Integrated health care system in Eastern Massachusetts Sample size: 57,865	Population density (not defined) Residential units per building	Positive SARS CoV 2 test: 1st Feb to 21st June 2020 Hospital admission among those positive Deaths among those in hospital	↑	Odds Ratio Population density Positive tests: 1.14 (1.03–1.27) Hospitalisation: 0.99 (0.80–1.24) Deaths: ns not included in full model Housing units *per* building Positive tests: ns Hospitalisation: >2 units OR 1.83 (1.01–3.31) but >1/3/5/10/20/50 units ns Deaths: ns	Age Sex Race Language Household Crowding Occupation Education Income Transport Testing Rate	Very low
Emeruwa 2020	New York pregnant women attending Presbyterian/Columbia University Irving Medical Center or Allen Hospital maternity units Sample size: 396	District level population density (no definition) Number of residential units per building	Positive SARS CoV 2 test: 22nd Mar to 21st April 2020	↓	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)	Individual level: Comorbidity –diabetes, hypertension Building level: Mean assessed value District level: Household Income Poverty Rate Unemployment Rate Household Membership Household crowding	Low
Gu 2020	Michigan Medicine health system: people tested and random controls Sample size: 5698 tested, 7168 non tested controls	Population density (1000 Persons per mile ^{2}) in census tract of residence	Positive SARS CoV 2 test; Hospitalisation with Covid19 diagnosis ICU admission with Covid19 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
Joseph 2020	Georgia, obstetric patients in 2 hospitals admitted for delivery Sample size: 1882	Population density of census tract In 2 bands	Positive SARS CoV 2 test: 20 April –29 July 2020	↑	Prevalence of positive test Less dense 3.1 (2.0–4.2) More dense 5.1 (3.7–6.5) P = .03	None	Very low
Vahidy 2020	Greater Houston Sample size: 20,228	Population density (per mile^2) of zip code cross tabulation area	Positive SARS CoV 2 test: 5th Mar to 31st May 2020	↑	Unadjusted Odds Ratio 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) GSEM model for race mediated through population density: OR 1.03 (1.01–1.05)	None for unadjusted figures GSEM model adjusted for age and sex	Very low
Grantz 2016	Chicago - 496 census tracts	Population density (per acre)	Influenza mortality per 1000 From 26 Sept 1918 to Nov 16, 1918	↓	Risk Ratio Mortality: 0.996 (0.994–0.997) Mortality decreased by 4.3% (95% CI = 3.1%, 5.5%) per 10% increase in population density Correlation coefficient For R number: 0.293 (0.249–0.306) p<.001 Weekly R number	Age Illiterate Homeowners Unemployment	Low

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Table 2 (*continued*)

Author Year	Setting	Measure of neighbourhood design	Primary outcome	Direction of effect for population density	Effect estimates (95% confidence interval)	Adjusted covariates	Quality (GRADE)
					population density ns for 6 of the 7 weeks.		
Lothrop 2017	Maricopa and Pima Counties, southern Arizona 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	↓	Incidence Rate Ratio Population density ED visits: 0.94 (0.89, 1.00 p<.05) Admissions: 0.50 (0.45, 0.57 p<.001) Percent attached homes ED visits: 1.04 (1.02, 1.06) p<.001 Admissions: 1.04 (1.00, 1.08) Percent mobile homes ED visits: 1.03 (1.01, 1.05) p<.01 Admissions: 1.04 (1.01, 1.08) p<.05	Socio-economic status Air pollution Overcrowding	Low
Sloan 2015	Middle Tennessee – Nashville and neighbouring counties – census tracts 1743 hospital admissions, 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	↑	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.

risk of transmission. All the Covid-19 studies were during the first wave of the pandemic, so case ascertainment may have been affected by availability of tests and testing policies. Of the studies of other respiratory infections, six found a positive and six a negative association with population density. However, in general, the effect strength was considerably low and adjustment for potential covariate varied between studies highly inconsistent.

3.3. USA

Table 2 presents 13 studies from USA. Ten of these investigated links between population density and Covid-19. Most of these adjusted for age, sex, and race. They also included co-variates such as measures of poverty or household income, unemployment, education, insurance status, household size, overcrowding, composite measures of neighbourhood disadvantage, working from home and internet access. The level and complexity of adjustment differed considerably among these studies. The Covid-19 studies recorded cases in the early stages of the pandemic, with the latest date of testing being July 2020. Early in the pandemic, testing was restricted, so they may have missed people with with a less severe disease.

Five studies of Covid-19 from USA used an ecological design. Two of them (DiMaggio et al., 2020; NYU Furman Centre 2020) compared zip codes in New York, one (Credit, 2020) considered 54 zip codes in Chicago and 177 in New York, one (Bryan et al., 2020) included 795 census tracts in Chicago, and one (Nguyen et al., 2020) included 7625 zip codes in 20 states. They compared cumulative rates in each area up to a date ranging from April to July 2020. In most studies the outcome measure was confirmed Covid-19 cases, but the Chicago study (Bryan et al., 2020), used mortality, and so only included the most severe cases. Data on cases came from various government, county and state resources, potentially with differing levels of ascertainment. The metrics for analysis differed between studies and included regression coefficient, rate ratio and incidence density ratio. A multi-state study (Nguyen et al., 2020) found a positive association between population density and Covid-19 infection with an estimated rate ratio varying from 1.01 to 1.04. One New York study reported a positive, non-significant association (DiMaggio et al., 2020), another reported a negative non-significant association (Credit, 2020). The third New York study found higher numbers of confirmed Covid-19 cases in areas with lower population density (NYU Furman Centre 2020). However, this was a purely descriptive study so the association may well be confounded by other factors. The Chicago study (Bryan et al., 2020) found an inverse association between Covid-19 mortality and population density. However, after adjusting for statistically associated covariates this association became less significant.

Five studies from USA used individual level data (Table 3), two of which studied pregnant women who were tested for SARS CoV-2 when they attended a labour and delivery unit in New York (n=396) (Emeruwa et al., 2020) or Georgia (n=1882) (Joseph et al., 2020). Results were conflicting, with one finding a positive association with population density (Joseph et al., 2020) and the other a negative association (Emeruwa et al., 2020).These studies only reported bi-variate regression results, so the associations may not persist after adjusting for factors associated with Covid-19 infection. In addition, transmission among pregnant women may differ from transmission among the general population.

The other three individual level studies from USA used the proportion of positive results in people tested in Eastern Massachusetts (n=57,865) (Cromer et al., 2020), Greater Houston (n=20,228) (Vahidy et al., 2020) and Michigan (n=5698) (Gu et al., 2020). All three found a positive association between test positivity and population density. The Massachusetts study (Cromer et al., 2020) reported a fully adjusted OR (95%CI) of 1.14 (1.03, 1.27) and the Michigan study (Gu et al., 2020) reported an OR (95%CI) of 1.07 (1.03, 1.11). The Greater Houston study (Vahidy et al., 2020) concluded that population density indirectly

Table 3
Studies in China

Author Year	Setting	Measure of neighbourhood design	Primary outcome	Direction of effect for population density	Effect estimates (95% confidence interval)	Adjusted covariates	Quality (GRADE)
Huang 2020	Hong Kong – 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 Covid-19 cases per 1000, locally transmitted cases only 27 Jan to 14 April 2020	↑	Poisson regression coefficient 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 = .015	Geographical features only	Very low
Liu 2020	Hubei province – 17 cities	Population density (per km^2)	Covid19 cases per 1000 Up to 16 April 2020	↑	Correlation coefficient R2=0.77, P < .005 - all cities R2=0.498, P < .005 - excluding Wuhan and Shennongjia	None	Very low
You 2020	Wuhan – 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 Covid-19 cases per 10,000 people Up to 22 Feb 2020	↑	Spatial Regression Analysis Population density 38.338 p<.01 Aged population density 0.021 p<.05 Construction land proportion 57.859 p<.01 Average building scale −0.025 p<.01 Public greenspace 2.079 p<.01 (estimates from spatial lag model - rec by authors)	Geographical features only	Very low
Jin 2020	Chinese neighbourhoods 4329 case neighbourhoods 17,316 controls 4.5 km away	Facilities within 1.5 km: Restaurant Shopping Centre Hotel Services (Travel Agent, Ticket Office, Job Centre) Recreational Facilities Public Transit Education Health services	Confirmed Covid-19 cases Jan 18 - April 30, 2020	NA	Odds Ratios 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)	All at city level: Population size GDP Unemployment Residential mobility	Very low
Liang 2003	Beijing	Population density based on 'urban', 'suburb' and 'far-suburb' categorisation	SARS incidence, mortality, case fatality per million March 2003	↑	Rates at Urban level: Incidence: 3.342/ million, Mortality: 0.309/ million, Case fatality: 9.2% Rates at Suburb level: Incidence: 2.162/ million, Mortality: 0.151/ million, Case fatality: 7.0% Rates at Far-suburb level: Incidence: 0.921/ million, Mortality: 0.057/ million, Case fatality: 6.2%	None	Very low

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Table 3 (*continued*)

Author Year	Setting	Measure of neighbourhood design	Primary outcome	Direction of effect for population density	Effect estimates (95% confidence interval)	Adjusted covariates	Quality (GRADE)
Xiao 2014	Changsha urban area, Hunan Province, China Case control study Sample size: 1957 cases	Population density At street/township level (per Ha in 3 bands) Public places within 1 km: Primary School Middle School Higher Education Places, Hospitals Business District Malls and market	Confirmed flu H1N1 May 2009–Dec 2010 (control is randomly generated space/time point)	↑	Odds Ratios Population density: 2.798 (CI 2.394–3.270 p<.001) for middle density 2.704 (CI 2.108–3.469 p<.001) for high density Places < 1 km: 5.578 (CI 4.65–6.69 p<.001) - higher education places 1.234 (1.046–1.457 p = .013) - middle school 1.417 (1.205–1.667 p<.001) - primary school	Geographical features only	Very low

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

mediated the effect of non-Hispanic Black race (OR [95%CI]: 1.03 [1.01, 1.05]) and Hispanic race (OR [95%CI]: 1.02 [1.01, 1.06]).

Three studies from USA considered respiratory infectious diseases other than COVID-19, all of which used ecological designs. They studied lower respiratory infections in children under 5 years in Arizona from 2005 to 2009 (Lothrop et al., 2017), deaths from the 1918 influenza pandemic in Chicago (Grantz et al., 2016) and influenza hospitalisations between 2007 and 2014 in Tennessee (Sloan et al., 2015). Two of these found a statistically significant negative association with population density (Grantz et al., 2016; Lothrop et al., 2017). The third (Sloan et al., 2015) found a statistically significant increase in hospital admissions for influenza in the highest density areas. However, this study adjusted only for age so the association may be confounded by other factors, including differences between areas in access to community healthcare which is likely to affect hospitalisation for influenza.

3.4. China

Table 3 presents 6 studies from China included in the review. Four studied Covid-19 but only three considered the association with population density (Huang et al., 2020; Liu, Yuan, et al., 2020; You et al. 2020). All three were ecological studies and they had widely varying units of analysis, ranging in size from tertiary planning units in Hong Kong, with average population size 25,000 people, to cities in Hubei province with a population size between 76,000 and 9.7 million inhabitants. There is likely to be significant heterogeneity of both population density and other characteristics within these areas. All three studies assessed only geographical features without adjustment for the characteristics of people living in each area and found a statistically significant positive association with population density. However, these findings should be interpreted with caution as it is unclear if these associations may be confounded by differences in the characteristics of residents in areas with differing population density.

Table 4
Studies in other countries

Author Year	Setting	Measure of neighbourhood design	Primary outcome	Direction of effect for population density	Effect estimates (95% confidence interval)	Adjusted covariates	Quality (GRADE)
Birenbaum-Carmeli 2020	Israel - all residential communities with population >5000 (approx. 197 municipalities)	Population density (per km^2)	Confirmed Covid-19 cases per 1000 Up to 2 June 2020	↑	Regression coefficient 0.00024 - An increase of 100 people per km^2 raises morbidity by 24 patients per 1000,000 (beta=0.439).	Socioeconomic status Elderly population Minority status (Jewish or Arab)	Very low
Olowokure et al. (2003)	West Midlands, children <5 yrs.	Resident population per km^2 by census enumeration district	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; **Hib:** Haemophilus Influenzae type B.

There were two studies from China of other respiratory infections, investigating influenza H1N1 (Xiao et al., 2014) and SARS (Liang and Mi 2003), respectively. The influenza H1N1 study was a case-control study conducted in municipal districts in Changsha (capital city of Hunan province). The SARS study was an ecological descriptive study, which compared SARS incidence in urban, suburban and far suburban settings. Both studies reported a positive association with population density, but neither adjusted for characteristics of residents in each area, affecting results robustness.

3.5. Other countries

Table 4 presents studies from countries other than the USA or China. There were only two studies, both ecological. A study of Israeli residential communities (Birenbaum-Carmeli and Chassida 2020) found a positive association between Covid-19 case rates and population density, reporting that an increase of 100 persons per km^2 raised the Covid-19 case rate by 2.4 cases per 100,000 persons. The study found that population density was positively associated with Covid-19 case rates in both Jewish and Arab communities. It also reported the counterintuitive results that higher proportions of older people and lower socioeconomic status were both statistically significantly associated with lower rates of Covid-19. The authors suggested that this could be because large families with children increased spread of infection. However, as they did not adjust for the child population in their analysis of population density, this is difficult to assess. In addition, a UK study (Olowokure et al., 2003) reported on haemophilus influenza type b (Hib) in children under 5 years in the West Midlands, before and after the introduction of Hib vaccine in the 1990s. Both before and after the vaccine, they found a statistically significant negative association with population density. However, the lack of adjustment for potentially confounding or mediating factors weakens the robustness of these associations.

3.6. Neighbourhood design features

The studies considered a wide range of other neighbourhood characteristics that may be associated with a compact city, including: housing units per building, housing scale and house type; walkability; active commuting; land use mix; density of, or proximity to, schools; density of, or proximity to, other facilities.

Seven studies reported associations with residential units per building, building scale and/or housing type. Four studies 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. They found either no association or a negative association with the number of units per building (Table 2). The authors of the Chicago study (Bryan et al., 2020) suggested that many affluent residents, who have a lower risk of Covid-19 for other reasons, live in densely populated areas containing multi-unit buildings (Table 2). Two studies from China considered associations between Covid-19 and building scale (You et al. 2020) or building height (Huang et al., 2020), which may indicate higher housing density (Table 3). These reached conflicting results. The USA study of hospitalisations for respiratory infection in children in Arizona (Lothrop et al., 2017) found a positive association with attached homes and mobile homes, but this could be confounded by socioeconomic factors (Table 2).

Three studies, from USA or Hong Kong, considered associations with walkability, active commuting or land use mix and reached conflicting results. The study of zip codes in Chicago and New York (Credit, 2020) adjusted for covariates and found that zip codes with higher levels of active commuting had lower rates of confirmed Covid-19 (Table 2). However, the larger study of over 7000 zip codes across 20 states found that indicators of walkability and land use mix both increased the rate of Covid-19 and single lane roads reduced the rate (Table 2). The Hong Kong study (Huang et al., 2020) found a negative association between land use mix and confirmed Covid-19 cases (Table 3).

Three studies, in USA or China, considered associations with proximity to or density of schools. A New York study (DiMaggio et al., 2020) found no statistically significant association between Covid-19 incidence density ratio and school density (Table 2). Two studies from China (Table 3) used a case-control design with geographical controls to consider the association between proximity or number of educational facilities and either Covid-19 (Jin et al., 2020) or H1N1 influenza (Xiao et al., 2014). The geographical case-control design may cause bias as, given equal risk of infection across the population, highly populated areas that are likely to have more facilities will also have more cases.

Three studies, all in China, studied the association with the density of, or distance to, commercial facilities with inconsistent findings (Table 3). Whereas the Hong Kong study (Huang et al., 2020) found inconsistent associations with the built-environmental variables, the other two studies (Jin et al., 2020; Xiao et al., 2014) found positive associations with all the variables that were included in the study. All three studies have methodological limitations as noted above, so results should be treated with caution.

4. Discussion

4.1. Density and transmission

Taking lessons from history, urban planning and design of built environments have played an important role in the transmission of infectious diseases. For example, John Snow used mapping to identify the pump responsible for spreading cholera, and subsequent improvements to housing and living conditions have reduced the risk of many infectious diseases (Vineis, 2018). Nowadays, some urban built environment characteristics have been identified to have health benefits, such as provision of public transportation, sidewalks, land use mix, green and blue spaces and walkable access to services. However, during the Covid-19 pandemic, some environmental factors such as public transportation hubs have been identified as potential sites of transmission (Liu, 2020; Hamidi et al., 2020).

To our best knowledge, this is the first systematic review that aims to assess the associations between respiratory virus infections (especially Covid-19) and environmental characteristics of a compact neighbourhood design including population density. In theory, living in a compact neighbourhood can bring multiple benefits (e.g., promoting physical activity, increasing social interaction and sharing public facilities), but it might increase transmission during the pandemic, if the higher density increases crowding, especially indoors, or increases the likelihood of face-to-face contact (Sharifi and Khavarian-Garmsir, 2020; Rocklöv and Sjödin, 2020). Following this concern, we found that studies reported conflicting findings on population and housing density. This could reassure urban designers and policymakers who are promoting compact and walkable neighbourhoods in many international cities, such as the 20-min neighbourhood in Scotland (Scottish Government, 2020) or 15-min neighbourhood in Paris (Tomorrow City, 2020).

It might seem counter-intuitive that higher population density was associated with lower rates of infection in some studies. One reason may be that people in denser, more walkable, neighbourhoods with more local amenities are better able to reduce their wider mobility and comply with social distancing. Two studies (Hamidi and Zandiatashbar, 2021; Chan, 2020) found that during social distancing restrictions, people living in compact areas reduced their journeys more than those in lower density areas. Hamidi and Zandiatashbar (2021) speculated that this may reflect better disease awareness, better internet infrastructure allowing online alternatives, and pedestrian access to essential shops and services in local areas, so that people can avoid large stores where more people gather. People in less densely populated suburban or rural areas may travel into city centres for work, retail and other services, mixing with people outside their area of residence.

Another possible explanation is that living in a compact neighbourhood can encourage physical activity. In Western cities, denser urban areas tend to be more walkable than areas of suburban sprawl (Sallis et al., 2016; Giles-Corti et al., 2016). It has been suggested that physical activity may enhance immunity (Nieman and Wentz, 2019) and therefore reduce susceptibility to Covid-19. For example, a UK study found that objectively measured physical activity reduced the odds of Covid-19 outcomes (Zhang et al., 2020). In addition, our included studies were all in the first wave of the pandemic when restrictions on testing may have meant that less serious cases were missed. The chronic diseases that are associated with physical inactivity are also associated with higher severity of Covid-19 (Liu et al., 2020; Nystoriak and Bhatnagar, 2018; Nishiga et al., 2020; Crisafulli and Pagliaro, 2020). Plausibly, residents of neighbourhoods that encourage physical activity may have been less likely to have severe disease and so less likely to be tested and receive a positive diagnosis.

Some of these factors vary in different contexts. Most of the studies came from USA or China, which adopted different policy responses to the pandemic. The USA adopted a mitigation strategy. States introduced local mitigation measures including closures of non-essential businesses and schools, which began to reopen again in May. About half of states had introduced mask mandates by August 2020. Testing was more restricted, particularly early in the pandemic (Chen et al., 2021). China adopted a containment strategy with strict lockdown in cities with cases, testing and isolation of cases and contacts (Gao & Zhang, 2021). These differences may impact on how the neighbourhood environment might affect transmission of Covid-19. Also, compared with most studies in western cities, the positive association between high density and physical activity may not apply in the same way in a Chinese context (Sun et al., 2020; Lu et al., 2017). These factors highlight the importance of understanding contextual differences when interpreting these findings.

Apart from population density, several studies investigated other aspects of neighbourhood design that are features of compact cities. These included the number of housing units per building or residential scale, walkability, land use mix, proximity to schools and other facilities, and indicators of quality. There was only a small number of studies that considered each of these characteristics and they mostly reached conflicting findings, so no clear conclusions can be drawn. Other authors have argued that other factors are more important, such as poverty, front line employment, patterns of commuting and household overcrowding (Kang et al., 2020; Hamidi et al., 2020). These may have complex associations with population density and other neighbourhood characteristics, and there are clearer pathways through which these factors can increase the transmission of respiratory infections.

Household overcrowding is an established risk factor for Covid-19 and other infections (Barker, 2020). We did not aim to study household size or overcrowding but several of the Covid-19 studies 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, and they all reported a positive association. Housing design features that may reduce transmission include low rise building forms (Megahed and Ghoneim, 2020), sufficient space to reduce overcrowding and allow home working (Fezi, 2020; Kang et al., 2020; Megahed and Ghoneim, 2020), ventilation (Fezi, 2020; Pinheiro and Luís, 2020), and touchless contact points (Pinheiro and Luís, 2020; Megahed and Ghoneim, 2020). We looked for studies relating to housing form but found limited evidence on this. The Covid-19 studies from USA found either no association or a negative association with the number of units per building but the 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.

4.2. Limitations of current research

As the Covid-19 pandemic is still ongoing, studies may have prioritised research speed over quality and depth in order to control the transmission, and a major limitation of our review is the overall poor quality of included studies. Most used an ecological design, some of which had a small number of units of analysis. An important limitation was a lack of control for covariates likely to influence Covid-19 rates, including age, socio-economic status and co-morbidity. Some studies set out to identify characteristics of people who had increased susceptibility - for example racial differences - and included few data on neighbourhood characteristics other than population density which was included as a presumed confounder or mediator (Vahidy et al., 2020; Gu et al., 2020; Credit, 2020). Conversely, studies that focused on neighbourhood design often did not control for the characteristics of the people living in different kinds of neighbourhoods. This means that the associations may be confounded, as characteristics of residents of densely populated areas will differ from those living in less densely populated areas. Where included, different measures were used for socio-economic status including median income (Credit, 2020; Nguyen et al., 2020), insurance status (Cromer et al., 2020), the poverty rate (Bryan et al., 2020; Cromer et al., 2020; Nguyen et al., 2020) and composite measures (DiMaggio et al., 2020; Gu et al., 2020; Birenbaum-Carmeli and Chassida, 2020). These different aspects of socioeconomic status may affect the risk of infection in different ways, so it is difficult to compare findings.

Proxies used as measures of transmission included test positivity, reported case rates, hospital admissions and mortality. Many Covid-19 cases are asymptomatic, and severity is strongly influenced by age and comorbidity, so studies using hospital admissions or mortality are particularly prone to bias. In settings without free universal healthcare, high-income people may be more able to afford testing and treatment. Low-income people with minor symptoms may also avoid testing if a positive test would mean losing time off work. Studies may also be biased by geographical access to testing. Early in the pandemic tests were often restricted to hospitals, which are often found in the densely populated centre of a city. This may mean that healthcare workers and their families, who are a high-risk group, are more likely to live in densely populated areas near the hospital. This may be another source of bias.

As we were interested in implications for the ‘compact city’ operationalised into 15- or 20- minute neighbourhoods, we sought studies at the city, sub-city or small neighbourhood level. However, within these studies the population sizes of the units used for analysis varied widely, ranging from 200 households in UK census enumeration districts (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 et al., 2020). The studies also used different indicators for the neighbourhood characteristics of interest, and some did not indicate the measure of population density they used. As several studies reported a high correlation between neighbourhood characteristics, it is difficult to disentangle their effects. The studies used different approaches to analysis and analysis metrics, so we were unable to synthesise results.

4.3. Future research agenda

Research on the links between neighbourhood characteristics and health is complicated by the multi-dimensional nature of these associations. A ‘healthy’ neighbourhood may be defined as being safe, attractive, affordable, environmentally and economically sustainable, socially cohesive, with accessible public open space, employment, education, shops and services, public transport, walking and cycling infrastructure (Badland et al., 2014). These characteristics may interact with each other, and each may affect multiple health determinants. The characteristics of people living in an area affect their health, independently of geographical features of neighbourhoods, but may also interact with elements of design. There is a lack of standard indicators to describe and measure features of neighbourhood environments in studies of their association with health. Studies from different disciplinary perspectives may use different variables and methods, and potentially reach conflicting findings for policymakers. In general, from a geography perspective, scholars often focus on 'place', studying the links between environmental factors and health without controlling for characteristics of the population. Public health researchers, on the other hand, focus more on 'people' and the demographic characteristics of resident populations with less consideration of environmental characteristics. Moreover, the physical characteristics of neighbourhoods change slowly over time making it difficult to plan and conduct longitudinal studies to assess these changes. This means that most available studies are cross sectional, with potential for reverse causality.

Established associations may differ by time period. Some urban design and policy features that are known to benefit health in normal circumstances may need to be re-examined for their impact during the Covid-19 pandemic. These associations may also vary at different time points in the pandemic. Studies of Covid-19 in our review reported findings early in the pandemic. This brings the potential for bias by the kinds of areas that the virus seeded to first, and by differences in testing policies between areas and at different time points. Also, as the world changes in other ways (e.g., new technologies), other environmental factors might need to be revisited to explore their multiple impacts on health in different times.

Most of the studies were from the USA or China. Neighbourhood contexts in these countries differ greatly from each other, and from other countries. There are no consistent definitions for neighbourhood characteristics and variables in the fields of urban planning and design, unlike the definitions in the field of medicine. We speculate that planning and design projects need to face different cultures and societies in different contexts, and scholars also have a different understanding of these characteristics. For example, a city with a 500 million population is a small city in China, unlike the small cities in the UK. However, as Covid-19 is a global issue, if we do not build consistent definitions and terms, we cannot discuss the results and findings from different counties and cities. As such, there is an urgent call in the intersection between public health and urban design for future pandemics. Finally, the current review considered only studies in high- and middle-income countries. There is a need to consider the relevance of the compact city, and to research similar associations with respiratory infections and other health outcomes, in low-income settings.

5. Conclusions

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 that are components of a compact city, 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.

As society and technology continue to evolve, convenient and fast transportation might accelerate transmission of infectious diseases and facilitate future pandemics' destructive power and frequency. Future research should use consistent measures and methods to study the links between neighbourhood design and transmission in different contexts and phases. Despite the inconsistent findings in our review, planning policy and urban design can help to reduce transmission – for example by facilitating physical distancing in both indoor and outdoor spaces, reducing the need to travel into crowded city centres by providing local working hubs, and providing sufficient affordable housing to prevent household overcrowding.

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Declaration of competing interest

None.

Statements

We published a report on this study on the UNCOVER group website of the University of Edinburgh (Ashcroft et al., 2021).

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Appendix A. Supplementary data

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