Moderation effect of urban density on changes in physical activity during the coronavirus disease 2019 pandemic

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A B S T R A C T

Various social distancing measures were carried out in many cities worldwide during the coronavirus disease 2019 pandemic (COVID-19). These measures have led to decreased physical activity levels and higher health risks among urban populations. Strong evidence has been established that built environment characteristics can stimulate physical activity and thus improve public health during non-pandemic periods. Urban density was arguably one of the most important built environment characteristics. However, little is known about whether high urban density amplifies or attenuates the decline in physical activity during the pandemic. Based on two-wave physical activity data collected before and during the pandemic (in January and May 2020, respectively), we used moderation analysis to compare the changes in physical activity levels between people living in low- and high-density neighborhoods. Our results showed that people living in low-density areas have a smaller decrease in physical activity conducted in neighborhood, compared to those living in high-density areas. Our findings suggest that a flexible and porous urban development strategy could enhance the resilience of a city during the coronavirus pandemic and beyond.

1. Introduction

Since its emergence in late December 2019, coronavirus disease 2019 (COVID-19) remains a global public health crisis. The World Health Organization (WHO) declared COVID-19 to be a global health emergency on January 30, 2020 and subsequently declared a global pandemic on March 11, 2020 (World Health Organization, 2020a, 2020c). To mitigate the human-to-human transmission of the virus, various restrictive social distancing measures have been implemented by governments worldwide. Besides, citizens have been urged to practice social distancing in public spaces and to avoid any crowded or unnecessary gatherings (Honey-Rosés et al., 2020).

Although these measures have decreased the overall infection rate, they have unavoidable adverse impacts on people's physical activity behaviors and health (J. F. Sallis, Adlakha, Oyeyemi, & Salvo, 2020). Several empirical studies have indicated a significant decrease in physical activities during the pandemic due to the closure of sports and recreational facilities, lockdown and quarantine measures, and stay-at-home policies (Constandt et al., 2020; Giustino et al., 2020; Lesser & Nienhuis, 2020). The decline in physical activity levels has negatively affected both the physical and mental health of people, especially in this particular pandemic situation (Lesser & Nienhuis, 2020; Sallis & Pratt, 2020; Sallis et al., 2020).

There is strong evidence that during the non-pandemic period, certain built environment characteristics increase physical activity and health outcomes across the neighborhood, district, city, and national scale (Ewing & Cervero, 2010; Handy, Boarnet, Ewing, & Killingsworth, 2002; Liu et al., 2020; Saelens et al., 2012; Yang et al., 2021). Areas with high urban density, mixed land use, accessible parks, and well-connected streets are more conducive to promote physical activity than others, and hence improve various health outcomes (Forsyth, Oakes, Schmitz, & Hearst, 2007; Lu, Xiao, & Ye, 2017; Sallis et al.,

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2016). So far, little is known about whether built environment characteristics have a similar effect, or at least slow down the decline of physical activity during the pandemic. There are only a handful of studies that have explored the role of urban parks in promoting physical activity behaviors during the pandemic (Heo, Lim, & Bell, 2020; Xie, Luo, Furuya, & Sun, 2020). As one of the most important built environment attributes in terms of promoting physical activity and health outcomes (Ewing & Cervero, 2010; Forsyth et al., 2007; Handy et al., 2002), it remains unclear about the role of urban density in physical activity changes under the COVID-19 pandemic. This critical knowledge gap may limit our opportunities to mitigate the decrease in physical activity caused by the current pandemic and future epidemics.

To address this important research gap, we explored the moderation effect of urban density on the impact of COVID-19 on the change in physical activity by using a longitudinal research design in Hong Kong, a typical high-density Asian city. Individual physical activity levels were collected both before and during the pandemic, and the participants' residential locations were classified into low- and high-density urban areas. We examined whether people living in high- or low-density neighborhoods experienced different levels of changes in physical activity under identical COVID-19 pandemic situations and related social distancing measures.

2. Literature review

2.1. Benefits of physical activity

It has been well-established that maintaining adequate physical activity levels improves human health. As recommended by WHO, adults should achieve more than 150 min of moderate-intensity physical activity or 75 min of vigorous-intensity physical activity per week (World Health Organization, 2020b). Achieving such physical activity level accumulates many health benefits, such as strengthen the immune system; reduce the risks of virus infection, cardiovascular disease, diabetes mellitus, obesity, hypertension, cancer, osteoporosis, and depression; and improve general health (Penedo & Dahn, 2005; Reiner, Niermann, Jekauc, & Woll, 2013; Warburton, Nicol, & Bredin, 2006). Moreover, physical activity is a powerful preventive medicine that can maintain the health status of patients suffering from chronic diseases, such as cardiovascular disease and type II diabetes (Jeon, Lokken, Hu, & Van Dam, 2007; Jordan, Adab, & Cheng, 2020; Mora, Cook, Buring, Ridker, & Lee, 2007).

Furthermore, regular physical activity may have enhanced health benefits during the COVID-19 pandemic. First, regular physical activity reduces the risk of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infection and limits the damage caused by COVID-19 (P. Chen et al., 2020). Second, such benefits are more pronounced for chronic disease patients, as these patients are associated with an increased risk of severe SARS-CoV-2 infection and mortality (Sallis & Pratt, 2020). Third, physical activity improves mental health during stressful events and crises (O'Connor, Raglin, & Martinsen, 2000; Powell et al., 2019; Ströhle, 2009). Therefore, experts believe that maintaining regular physical activity could also mitigate the potential mental stress caused by the pandemic (Sallis & Pratt, 2020).

2.2. Urban density-physical activity associations

In a socio-ecological model, physical activity is affected by various factors, such as individual characteristics, social environment, and built environment to which a person is exposed (Sallis et al., 2006; Stokols, 1996). Therefore, the attributes of a built environment, such as the urban forms, transportation, and land-use patterns, can directly impact individuals' engagement in physical activity (McLaren & Hawe, 2005). In previous built environment–physical activity studies, researchers have examined various built environment attributes, especially those corresponding to the "Ds" framework: density, diversity, design, destination accessibility, and distance to transit (Cervero & Kockelman, 1997; Ewing & Cervero, 2010). Systematic reviews have shown that the urban density, land-use mix, connectivity, and pedestrian-oriented design features are significantly positively correlated with physical activity engagement (Hoehner, Ramirez, Elliott, Handy, & Brownson, 2005; McCormack, Giles-Corti, & Bulsara, 2008; Xiao et al., 2020; Yang et al., 2019).

Among the "Ds" framework, density is regarded as one of the most important factors because it directly affects active transport and indirectly acts as a proxy for other variables such as socioeconomic status (SES), transit use, and land-use mix (Cervero & Kockelman, 1997; Forsyth et al., 2007; Handy et al., 2002). Density can be defined as the number of households, population members, or jobs distributed per unit area (Tomey, 2005). The results of previous cross-sectional studies have supported a positive association between urban density and physical activity (Cervero & Landis, 1997; Forsyth et al., 2007; Handy et al., 2002). More rigorous evidence was also derived from longitudinal studies. An increase in population density is associated with increases in the walking trip frequency (Hino, Usui, & Hanazato, 2020; Joh, Chakrabarti, Boarnet, & Woo, 2015; Tewahade et al., 2020), total walking distance (Sun, Oreskovic, & Lin, 2014), and transportation-related cycling (Beenackers et al., 2012). For example, an analysis of the longitudinal data of 20,354 black women who relocated to a neighborhood with a higher population density revealed an increase in the weekly time spent walking for transportation and recreation (Coogan et al., 2009). Also, an analysis of longitudinal samples from Norfolk, USA revealed that residents who lived in areas with a higher job density performed better in maintaining active commuting (Yang, Griffin, Khaw, Wareham, & Panter, 2017). Similar evidence was also reported for students from Washington, USA (Chen, Jiao, Xu, Gao, & Bischak, 2018). Overall, these studies have shown a positive association between urban density and physical activity.

2.3. Moderation effect of built environment characteristics

Moderation effect forms the core of socio-ecological models (Ding & Gebel, 2012; Van Cauwenberg et al., 2011). Moderation is a theory for understanding and refining a causal relationship between the independent variable and dependent variable (Wu and Zumbo, 2007). With moderation analysis, researchers can understand under which condition an independent variable has the strongest or weakest effect on a dependent variable. In essential, a moderator is the third variable that modifies the strength or direction of the causal effect (Wu and Zumbo, 2007). According to socio-ecological models, besides its direct impact on physical activity, the built environment acts as a moderator between other determinators and physical activity, although their work did not focus on urban density (McLaren & Hawe, 2005). For example, a British study reported that the link between socioeconomic status and mortality is moderated by the amount of green spaces in a neighborhood (Mitchell & Popham, 2008). The link was stronger in areas with fewer green spaces and was weak in areas with more green spaces. Furthermore, a recent review concluded that built environment attributes moderate the relationship between disability and physical activity (Eisenberg, Vanderbom, & Vasudevan, 2017). Poor lighting and barriers can aggravate the negative effects of having a disability on physical activity (Eisenberg et al., 2017). In addition, a recent nationwide study in the USA revealed that the racial disparity (the white vs. the black) in SARS-CoV-2 infection rate was significantly smaller in counties with a higher ratio of green spaces (Lu et al., 2021).

Therefore, from a theoretical perspective, it is necessary to examine how built environment characteristics moderate the relationship of other factors and health outcomes in order to deliver ecologically valid evidence for urban planning and design (Magill, 2011).

2.4. Decline of physical activity during the pandemic

Before the implementation of population-level vaccination against COVID-19, social distancing and lockdown remain the most effective measures (Megahed & Ghoneim, 2020; Sun & Zhai, 2020). Various social distancing measures have been adopted by governments worldwide, including the closure of unessential business services and community facilities (such as parks and playgrounds) and requiring citizens to stay at home (Honey-Rosés et al., 2020).

Such social distancing measures and fear of virus infection risks inevitably decrease urban residents' physical activity levels (Constandt et al., 2020; Giustino et al., 2020; Lesser & Nienhuis, 2020; Sekulic, Blazevic, Gilic, Kvesic, & Zenic, 2020). A study conducted in Canada found that 40.5 % of inactive participants and 22.4 % of active participants reported lower physical activity levels during the pandemic (Lesser & Nienhuis, 2020). Another study conducted in Belgium also indicated an increase in sedentary behaviors, such as watching TV, laying down, and sitting (Constandt et al., 2020). Moreover, among people who were highly active before the COVID-19 outbreak, those older than 55 years, those with lower education degrees, and those who participated in sports club activities were found to participate in less exercise during the pandemic (Constandt et al., 2020). Besides, a significant decrease in the total energy expenditure and physical activity level was observed in Italy (Giustino et al., 2020).

2.5. Research gap and our contribution

To better cope with the COVID-19 pandemic and related decline in physical activity, it is essential to rethink the way we develop and design cities to ensure the health and safety of urban residents. Previous pandemics have transformed our cities, as architects and urban planners redesigned buildings and urban forms to cope with such pandemics (Chang, 2020; Dejtiar, 2020; Muggah & Ermacora, 2020). For example, the modern sewage system and greenspace design in cities were largely driven by public health concern caused by the pandemics occurred in 19th centuries (Budds, 2020; Klaus, 2020).

So far, several studies are exploring the role of the built environment in reducing virus transmission during this COVID-19 pandemic, such as building ventilation system (Megahed & Ghoneim, 2020), spatial layout (Megahed & Ghoneim, 2020), urban density (Allam & Jones, 2020), greenspaces (Honey-Rosés et al., 2020), and land use diversity (Gürdür Broo et al., 2021). However, little is known about the moderation effect of urban density on the decline of physical activity during the pandemic. There is some indirect circumstantial evidence to support the proposition that urban density may modify the impact of the COVID-19 pandemic on physical activity. For example, the mobility reduction was significantly lower in areas with more parks during COVID-19 for Maryland and California, USA (Heo et al., 2020). Based on a survey in Chengdu, China, it is found that urban parks and open spaces can afford safe outdoor activities and improve overall health (Xie et al., 2020).

In summary, we identified two major research gaps. First, the COVID-19 pandemic and related social distancing measures have a significant negative impact on physical activity. However, it remains unclear whether urban density could moderate this impact. In other words, it remains unclear whether people living in high- or low-density neighborhoods experienced the same levels of change in physical activity under the COVID-19 pandemic and related social distancing measures. This critical knowledge gap may limit our opportunities to mitigate the decrease in physical activity caused by the current pandemic and future epidemics.

Second, very few longitudinal analyses related to physical activity changes during the pandemic have been conducted, especially in high-density Asian cities. The built environments and social contexts in Asian cities often differ from those in low-density cities in Western countries. For example, Asian cities often feature higher urban densities, close social ties, and more active lifestyles. Therefore, it is important to investigate the changes in physical activity during the pandemic in high-density Asian cities.

To address the abovementioned gaps, we explored the moderating role of urban density on the impact of COVID-19 on physical activity by using a longitudinal research design. Individual physical activity levels were collected both before and during the pandemic, and the participants' locations were classified into low- and high-density urban areas. Fig. 1 shows a conceptual model of the interactions between urban density, COVID-19 pandemic, and physical activity. The urban density was treated as the moderator in this model. We hypothesized that a low urban density would mitigate the negative impact of COVID-19 social distancing measures on physical activity levels. For one reason, residents in high-density areas may have higher virus infection risks and hence would less likely to perform outdoor activities.

This study makes the following three contributions to the literature and society. 1) Theoretically, it was one of the first studies of the moderation effect of urban density on the relationship between COVID-19 and physical activity. 2) Methodologically, a longitudinal design was adopted to better understand the rigorous association between urban density and physical activity changes in Asian cities. 3) This study also has important planning implications. To address the sharp global decrease in physical activity during the current pandemic and potential future crises, it is vital to identify the potential built environment attributes that can mitigate a decrease in physical activity to create resilient and healthy cities.

3. Materials and methods

3.1. Research design

Hong Kong is a high-density coastal city located in the southeastern region of China. As of 2016, the gross population density of Hong Kong had reached 6777 persons/km². Hong Kong has a hilly terrain, and more than 75 % of the land has been left in a relatively natural state, such as country parks or protected areas. Thus, the population density has reached more than 26,000 persons/km² in the urban built-up areas.

In late January 2020, the Hong Kong government released an emergency-level notice of the COVID-19 outbreak, appealing to its citizens to stay at home and avoid going out and unnecessary social interactions. During our study period, all public land sports and aquatic facilities, private fitness clubs, and facilities in public parks which involve touch (e.g., fitness center, children playground) were temporarily closed. However, open areas or trails in public parks, greenways, country parks, public transport and daily commercial services were under normal operation.

The virus outbreak and changes in public policy allowed us to collect physical activity data before (T_1) and during (T_2) the pandemic for participants who lived in neighborhoods with different urban density levels. All participants experienced the same virus outbreak and related social distancing measures. Hence, we could observe the changes in physical activity levels in two groups of participants (those living in high- vs. low-density neighborhoods) during two time periods (T_1 and T_2) and whether the population density could moderate the negative effects of COVID-19 on physical activity (Fig.1).

The physical activity data were collected during two wave periods: baseline (T_1) and follow-up (T_2). The baseline data were self-reported before the virus outbreak in Hong Kong and corresponded to the period between January 6th and 10th, 2020. The follow-up data were self-reported during the virus outbreak between May 9th and 13th, 2020. Only participants who completed both the baseline and follow-up self-reports were included in the study. Finally, 661 residents were recruited. Of these, 330 lived in high-density neighborhoods, and 331 lived in low-density neighborhoods.
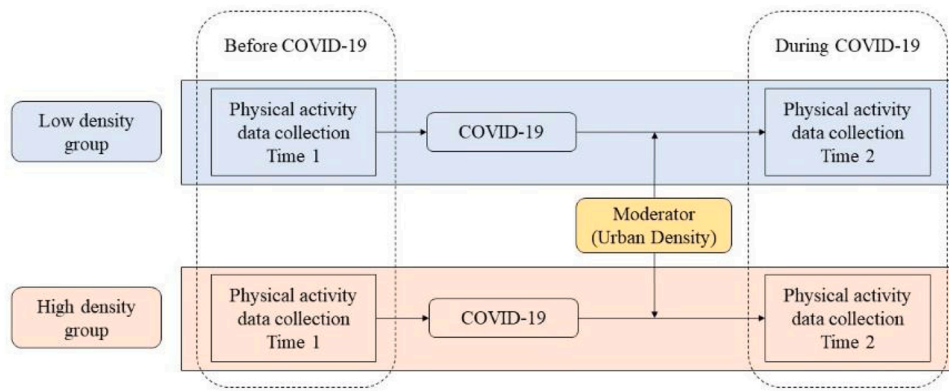
Fig. 1. The research framework in this study. We collect physical activity outcomes of residents in low- and high-density neighborhoods before and during the COVID-19 pandemic.

3.2. Study area and participants

The study areas were selected using a multistage stratified sampling method. First, as a proxy of urban density, we used population density, which is defined as the resident population per unit of land area in tertiary planning units (TPUs) in Hong Kong. A TPU is a spatial unit demarcated by the Planning Department of the Government of Hong Kong S.A.R for town planning purposes and as a basic census statistics unit. As mentioned above, approximately 75 % of all land in Hong Kong is protected for conservation or nature-related purposes; thus, all TPUs in urban built-up areas were used for this classification.

Second, the TPUs in the built-up areas were divided into quantiles based on the population density. We defined the two highest quantiles as the high-density areas and the two lowest quantiles as the low-density areas.

Third, nine TPUs each were randomly selected from the high- and low-density areas. Considering the district administration system in Hong Kong, these selected neighborhoods were relatively well-distributed across Kowloon, Hong Kong Island, and the New Territories. Figs. 2 & 3 shows the distribution and enormous variation of population density in Hong Kong.

Fourth, trained interviewers visited public spaces of the selected neighborhoods and interviewed participants with a convenient sampling method. The sample size of each neighborhood was approximately 35–40, and all the interviews were carried out in a fixed time period from 2 pm to 5 pm.
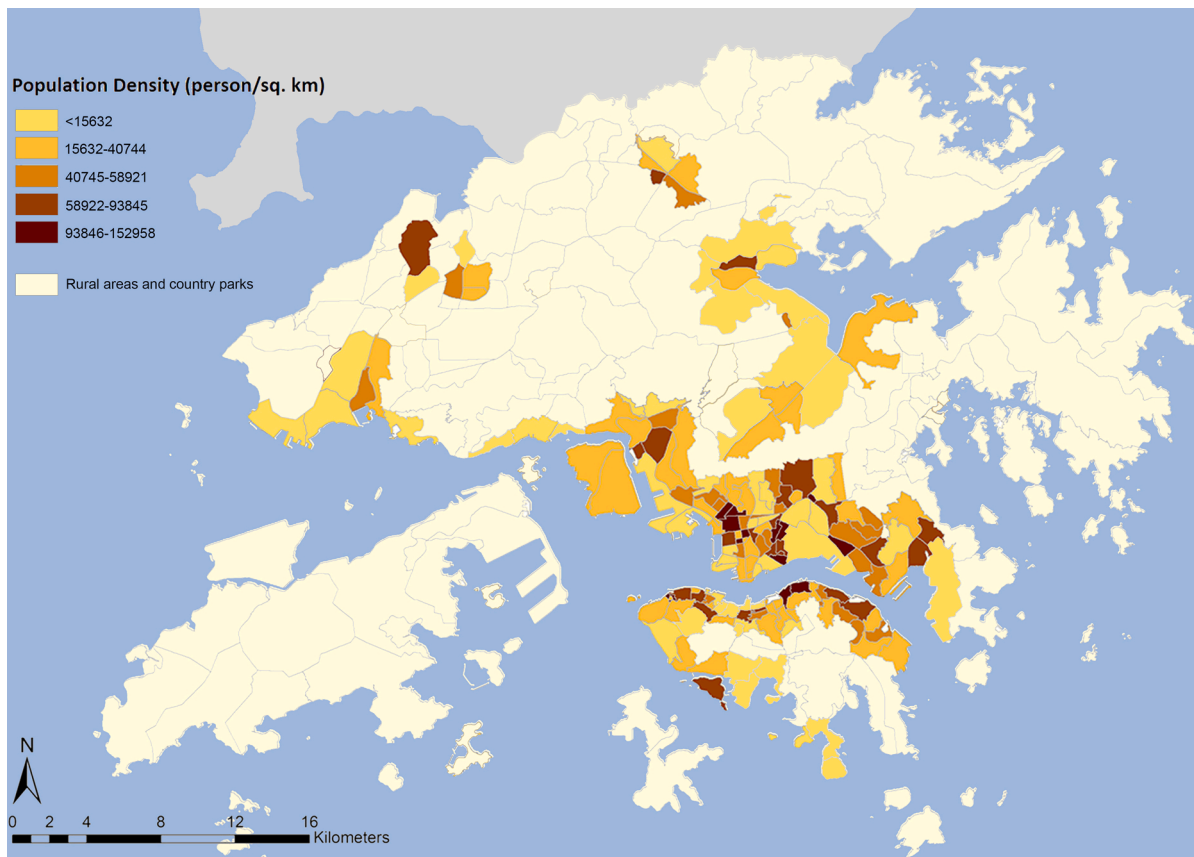

Fig. 2. Tertiary planning units in built-up areas were divided into quantiles based on the population density. The two highest quantiles were defined as the high-density areas and the two lowest quantiles as the low-density areas.

Fig. 3. Examples of study areas with low and high urban density in Hong Kong.

3.3. Physical activity

During both baseline (T_1) and follow-up (T_2) interviews, the interviewers asked six identical questions adopted from the International Physical Activity Questionnaire to assess the individual physical activity levels (Craig et al., 2003): 1) "During the past seven days, how many days did you engage in physical activity in your neighborhood?" 2) "Of those days, how much time did you spend on engaging in physical activity in your neighborhood?" 3) "During the past seven days, how many days did you visit the country parks?" 4) "Of those days, how much time did you spend on visiting the country parks?" 5) "During the past seven days, how many days did you engage in physical activity at home?" 6) "Of those days, how much time did you spend on engaging in physical activity at home?"

3.4. Covariates

Demographic data, including age (year), gender (male/female), education level, and family monthly income (Hong Kong dollars), were also collected as potential covariates for the analysis. The age was converted into a four-band variable (<18, 18–44, 45–64, 65 and above). The education level was also converted into a four-band variable (primary school and under, middle school, high school, and post-secondary and above). The family monthly income was categorized into five-band variables (≤HK\$10,000, 10,001–20,000, 20,001–30,000, 30,001–50,000, 50,001 and above). Neighborhood-level built environment covariates, including land use mix, street connectivity, and the number of recreation facilities, were collected as well. Street connectivity was defined as the density of street intersections.

3.5. Statistical analysis

The data analysis involves two steps. First, we used paired *t*-test to explore whether there were significant changes (T_2 vs. T_1) of physical activity in neighborhood, at home, in country park based on the residents in low-density neighborhoods and high-density neighborhoods, respectively.

Second, moderation analysis was conducted to examine whether the decline in physical activity was moderated by urban density. As we described in the literature review section, a moderator (urban density in this study) is the third variable that modifies the strength of the effect of an independent variable on a dependent variable (COVID-19 pandemic on physical activity). The moderation analysis is characterized statistically as an interaction effect between the moderator and the independent variable (urban density * COVID-19). Because our moderator is a categorical variable, the proper statistical method is the two-way factorial ANOVA, and the moderation effect is represented by a significant interaction effect (Baron & Kenny, 1986).

$$Y_{it} = \beta_0 + \beta_1 P_t + \beta_2 M_i + \beta_3 P_t M_i + \beta_4 Covariates_i$$

where Y_{it} is the physical activity outcome observed for participant i at

time period t, M_i is the indicator of participant i being in the high-density neighborhood group (vs. low-density neighborhood group), and P represents the time periods before and after the pandemic (T_1 vs. T_2). The parameter β_3 indicates the interaction between the population density and the COVID-19 pandemic, which estimates the moderation effect. $Covariates_i$ indicates a vector of individual and neighborhood covariates. We also plotted out the regression of physical activity on the pandemic situation at both levels of urban density (high vs. low density) to visualize the effect of the moderator. All analyses were conducted in Stata 16.0 (StataCorp LLC., College Station, TX, USA).

4. Results

4.1. Characteristics of our participants

Table 1 shows the descriptive statistics of our participants. The age structure and gender ratio were similar for participants living in high- and low-density neighborhoods. However, the participants living in high-density neighborhoods tended to have a higher education level and family income than those living in low-density neighborhoods. It is

Table 1
Descriptive statistics results of participants living in high-density vs. low-density neighborhoods (N = 661).

Characteristics	Participants living in high-density neighborhood (n = 330)	Participants living in low-density neighborhood (n = 331)
Individual level (count (%))		
Age Group (years)		
<18	60 (18.2)	90 (27.2)
18–44	145 (43.9)	138 (41.7)
45–64	75 (22.7)	56 (16.9)
≥65	50 (15.2)	47 (14.2)
Female	161 (48.8)	170 (51.4)
Education		
Primary school or under	89 (27.0)	86 (26.0)
Middle school	54 (16.4)	53 (16.0)
High school	79 (23.9)	103 (31.1)
Postsecondary	108 (32.7)	89 (26.9)
Family House Income (HKD)		
≤10,000	57 (17.3)	86 (26.0)
10,001–20,000	44 (13.3)	74 (22.4)
20,001–30,000	91 (27.6)	107 (32.3)
30,001–50,000	92 (27.9)	58 (17.5)
>50,001	46 (13.9)	6 (1.8)
Neighborhood level (Mean (SD))		
Land use mix	0.56 (0.27)	0.42 (0.17)
Street connectivity (count/ km²)	97.06 (58.88)	51.51 (14.95)
Recreation facilities (count/ km²)	58.45 (28.12)	37.93 (18.98)
Population Density (persons/km²)	84,064 (22,522)	29,806 (10,991)

worth noting that the average population density in high-density neighborhoods reaches 84,064 persons/km^2, almost triples that in low-density neighborhoods.

4.2. Changes in physical activity

Table 2 shows the physical activity levels before (T$_1$) and during (T$_2$) the COVID-19 pandemic, as well as changes in physical activity levels (T$_2$-T$_1$) for two groups of participants. For all participants, physical activity levels conducted in neighborhood significantly decreased during the pandemic (change= -28.3 min.). There is a barely significant increase in physical activity conducted in country parks (change = 6.1 min.). There is no significant change in physical activity conduct at home. For participants living in high-density neighborhood, there is a significant decrease in the physical activity conducted in neighborhood (change= -46.4 min.). For participants living in low-density neighborhood, there is a significant increase in the physical activity conducted in country park (change = 12.2 min.).

4.3. Moderation effect

Table 3 presents the estimations for the moderation effect analysis. After adjusting for the individual covariates and built environment covariates, a significant moderation effect of population density was found on the change in the level of physical activity performed in the neighborhood ($p < 0.05$). People living in a low-density neighborhood exhibited a smaller decrease in the duration of physical activity conducted in neighborhood, compared with people living in a high-density neighborhood. Fig. 4 illustrates the effects of the pandemic situation on the physical activity conducted in neighborhood at both levels of urban density, which shows different slopes for these living in high and low urban density.

No significant moderation effect of the population density on the duration of physical activity performed in country parks or at home was observed.

5. Discussion

The outbreak of COVID-19 and the implementation of social distancing measures led to a sharp decrease in the physical activity level,

Table 2
Changes in physical activity outcomes. Mean and standard deviation in minutes were reported.

	High density (N = 330)	Low density (N = 331)	Total (N = 661)
Duration of physical activity in neighborhood			
T$_1$ [Mean (SD)]	231.1 (187.3)	139.7 (107.0)	185.3 (159.1)
T$_2$ [Mean (SD)]	184.7 (143.7)	129.5 (122.1)	157.0 (136.1)
Change (T$_2$-T$_1$)	−46.4 (125.8) ***	−10.2 (101.6)	−28.3 (115.6) ***
Duration of physical activity in country park			
T$_1$ [Mean (SD)]	79.9 (120.6)	62.7(102.5)	71.3 (112.2)
T$_2$ [Mean (SD)]	79.9 (126.2)	74.9 (117.6)	77.4 (121.9)
Change (T$_2$-T$_1$)	0.0 (108.7)	12.2 (113.6) **	6.1 (111.2) *
Duration of physical activity at home			
T$_1$ [Mean (SD)]	71.8 (104.2)	57.1(82.1)	64.4 (94.0)
T$_2$ [Mean (SD)]	64.1 (98.9)	54.2 (72.2)	59.1 (86.7)
Change (T$_2$-T$_1$)	−7.7 (92.9)	−2.9 (48.7)	−5.3 (74.1)

Note: The paired t-tests were conducted to compare the participant's physical activity levels during T$_1$ and T$_2$. The results are labeled with asterisks in the rows showing the change. *p < 0.1, ** p < 0.05, *** p < 0.001.

Table 3
Moderation effect of population density on the change in physical activity caused by the coronavirus disease 2019 outbreak.

	Estimate	p-value
Duration of physical activity in neighborhood	−36.208	0.021**
Duration of physical activity in country park	−4.785	0.342
Duration of physical activity at home	−12.111	0.342

Note *p < 0.1, ** p < 0.5, ***p < 0.001.

which attracted the attention of public health officials and researchers (J. F. Sallis et al., 2020). However, the impact of urban density on physical activity changes during the pandemic remained unclear, especially in a high-density urban context. By using a longitudinal study and moderation analysis to address these research gaps, we yielded two major findings.

First, for all participants, the duration of physical activity performed at home and in the neighborhood decreased during the pandemic. However, there was a statistically insignificant increase in physical activity duration in country parks, especially for those living in low-density neighborhoods. This finding concurs with those of other recent studies, which showed that recreational activities in green spaces increased during the COVID-19 pandemic (Lu, Zhao, Wu & Lo, 2021; Venter, Barton, Gundersen, Figari, & Nowell, 2020). The closure of community amenities, public sports facilities, and fitness clubs led people to change their preferred physical activity venues from neighborhood facilities to outdoor green spaces (Lu, Zhao, Wu & Lo, 2021; Neto et al., 2020). Although the government and public health experts regularly encourage citizens to engage in physical activity, it is difficult to conduct regular exercises at home (Neto et al., 2020). Such issues may be aggravated in high-density cities, such as Hong Kong. For instance, the average living space available in public housing in Hong Kong is only 13.4 m^2/person. Given the current global crisis, green spaces in or nearby cities can be regarded as suitable alternative physical activity venues for improving health and as relaxing spaces to escape from the daily stress and potential virus infection risk during the COVID-19 pandemic (Austenfeld & Stanton, 2004; Taylor & Stanton, 2007; Venter et al., 2020).

Second, we also observed a significant moderation effect of population density on the change in physical activity conducted in the neighborhood. People living in low-density neighborhoods had a smaller decrease in physical activity than those living in high-density neighborhoods. This finding indicates that a low urban density potentially mitigated the negative effect of the COVID-19 pandemic on physical activity performed in the neighborhood. This result is in line with a recent study conducted in Canada, which reports that youth living in low-density neighborhoods encouraged outdoor physical activities during the pandemic, though that studies did not conduct moderation analysis (Mitra et al., 2020). There are three tentative explanations for this finding: a) the association between the population density and the real or perceived risk of virus infection, b) the closure of indoor physical activity facilities, and c) the use of different transportation modes in different areas.

a) Person-to-person contact has been confirmed as the major transmission mode of SARS-CoV-2 (Klompas, Baker, & Rhee, 2020; Zhang, Li, Zhang, Wang, & Molina, 2020). In a study conducted in China, SARS-CoV-2 transmission was shown to occur mostly through close human contact (Qian et al., 2020). People living in high-density areas might have a higher possibility of interaction with others and would thus face a higher human-to-human transmission risk than those living in low-density neighborhoods, both intentionally and unintentionally (Kocak Tufan & Kayaaslan, 2020). Therefore, people living in high-density neighborhoods may not be willing to expose themselves to a crowded neighborhood environment to perform physical activity. Conversely, it is easier for people living in low-density neighborhoods to adhere to social distancing measures when performing physical activity
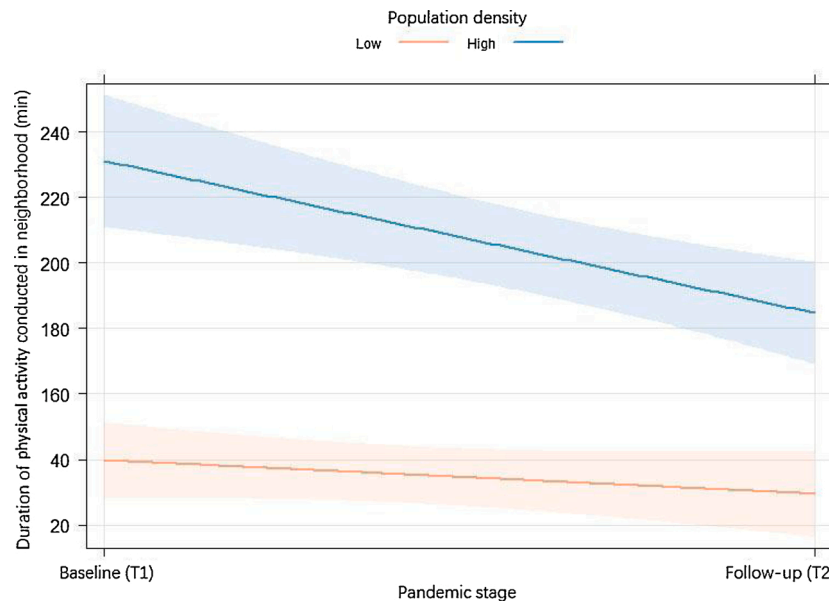
Fig. 4. Changes in physical activity (physical activity) performed in the neighborhood for two groups (high-density vs. low-density). People living in low-density areas had a smaller decline in physical activity conducted in neighborhood, while people in high-density areas had a larger decline.

in the neighborhood because they have more outdoor space per person; this means a less-crowded neighborhood environment and a lower risk of virus infection.

b) Most of the indoor sports and recreational facilities in Hong Kong, such as sports centers, private fitness centers, and gyms, are located in high-density urban areas. Thus, when the government announced the closure of these facilities, people living in high-density neighborhoods received a larger impact than those living in low-density neighborhoods, which have fewer such facilities. On the other hand, low-density neighborhoods tend to have more open green spaces (e.g., parks and greenways), which remain open in Hong Kong during the study period. Hence, people in low-density neighborhoods can still access such green spaces for physical activity.

c) Residents living in areas with different densities may have different transportation mode choices, and these might have been different levels affected during the pandemic. Evidence has shown that people living in low-density communities are more inclined to travel by private car, whereas those living in high-density communities prefer to walk or use public transportation (Nguyen, Kato, & Phan, 2020; Sun, Ermagun, & Dan, 2017). During the COVID-19 pandemic, the use of public transportation and walking plummeted due to concerns about overcrowded spaces and virus infection, whereas driving was less affected (Beck & Hensher, 2020; De Vos, 2020). Thus, walking for transportation purposes may have decreased among people living in high-density neighborhoods, leading to a reduction in total physical activity in neighborhoods.

Urban density is a key planning factor that significantly impacts urban social and economic activities (Lu, Sun, Gou, Liu, & Zhang, 2019). Traditional and contemporary urban planning theories often advocate high urban densities for various reasons. High-density urban development is one of the most efficient approaches and benefits both commercial development and the urban quality of life (Luo, O'Connor, & Enquist, 2016). Moreover, a high-density urban form promotes social equality by promoting lifestyle benefits for people in low-income groups, such as improved public transport, better access to facilities, and reduced social segregation (Burton, 2000).

However, our study results suggest that a low urban density provided resilience to the decreases in physical activity observed in urban residents during the COVID-19 pandemic. There is emerging evidence that the COVID-19 infection rate tends to be higher in high-density cities

(DiMaggio, Klein, Berry, & Frangos, 2020; Huang et al., 2020; Stier, Berman, & Bettencourt, 2020), suggesting that an open and porous urban structure produces a more resilient city that can face the challenges of viral pandemics. Scholars in public health and urban studies have already called for a reconsideration of the development and (re) design strategies in our cities when coping with pandemics. Some have argued that more street space should be liberated for pedestrians and cyclists, which would move us closer to greener cities (Nieuwenhuijsen, 2020). Others have highlighted the importance of urban green spaces, especially those that serve as refuges in densely populated and bustling cities (Lu, Zhao, Wu & Lo, 2021; Venter et al., 2020). Hence, public health officials should shift their focus from policies of social distancing to policies that incorporate a proper urban form as an effective intervention strategy to combat virus outbreaks (Honey-Rosés et al., 2020; Venter et al., 2020).

This study also has several limitations. First, people tend to over-report their physical activity levels, which is a common bias to collect physical activity levels with surveys (Sallis & Saelens, 2000). Future studies may objectively measure physical activity levels, such as via accelerometers. Second, the follow-up data were collected only five months after the baseline data. Future studies may be needed to investigate the potential long-term changes in physical activity, given that the global COVID-19 pandemic is still ongoing at the time of writing. Third, some other potential factors that may affect the relationship between COVID-19, urban density, and physical activity, such as the number of COVID-19 cases, indoor thermal comfort, and air quality, were not analyzed in this study (Megahed & Ghoneim, 2020; Raj, Velraj, & Haghighat, 2020). Finally, this study was conducted in a single city. The high urban density in Hong Kong may limit the potential generalizability and transferability of the current findings. Evidence from other cities, especially those with a medium or low density, is required to verify our findings.

6. Conclusion

We adopted a longitudinal study design to evaluate the moderation effect of urban density on the relationship between the COVID-19 pandemic and physical activity. This is one of the first studies to examine the moderation effect of urban density on physical activity changes during this pandemic. Our findings indicate that the current

COVID-19 pandemic and the implementation of related social distancing measures have negatively impacted physical activity levels, except physical activity duration in country parks. Furthermore, a lower urban density mitigated the negative impact of the COVID-19 pandemic on the change in physical activity performed in neighborhoods. Based on our findings, we tentatively suggest that a flexible and porous urban development strategy, such as urban development with adequate green and open space reservation, should be emphasized in future urban planning practices to avoid the risk of virus outbreaks and to promote a sustainable urban future.

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Declaration of Competing Interest

The authors declare that they have no competing interests.

References

Allam, Z., & Jones, D. S. (2020). Pandemic stricken cities on lockdown. Where are our planning and design professionals [now, then and into the future]? *Land Use Policy, 97*, 104805. https://doi.org/10.1016/j.landusepol.2020.104805

Austenfeld, J. L., & Stanton, A. L. (2004). Coping through emotional approach: A new look at emotion, coping, and health-related outcomes. *Journal of Personality, 72*(6), 1335–1363. https://doi.org/10.1111/j.1467-6494.2004.00299.x

Baron, R. M., & Kenny, D. A. (1986). The moderator mediator variable distinction in Social Psychological-Research - conceptual, strategic, and statistical considerations. *Journal of Personality and Social Psychology, 51*(6), 1173–1182. https://doi.org/10.1037/0022-3514.51.6.1173

Beck, M. J., & Hensher, D. A. (2020). Insights into the impact of COVID-19 on household travel and activities in Australia - the early days under restrictions. *Transport Policy, 96*, 76–93. https://doi.org/10.1016/j.tranpol.2020.07.001

Beenackers, M. A., Foster, S., Kamphuis, C. B. M., Titze, S., Divitini, M., Knuiman, M., … Giles-Corti, B. (2012). Taking up cycling after residential relocation built environment factors. *American Journal of Preventive Medicine, 42*(6), 610–615. https://doi.org/10.1016/j.amepre.2012.02.021

Budds, D. (2020). *Design in the age of pandemics*.

Burton, E. (2000). The compact city: Just or just compact? A preliminary analysis. *Urban Studies, 37*(11), 1969–2006. https://doi.org/10.1080/00420980050162184

Cervero, R., & Kockelman, K. (1997). Travel demand and the 3Ds: Density, diversity, and design. *Transportation Research Part D-Transport and Environment, 2*(3), 199–219. https://doi.org/10.1016/s1361-9209(97)00009-6

Cervero, R., & Landis, J. (1997). Twenty years of the Bay Area Rapid Transit System: Land use and development impacts. *Transportation Research Part a-Policy and Practice, 31*(4), 309–333. https://doi.org/10.1016/s0965-8564(96)00027-4

Chang, V. (2020). *The post-pandemic style*. Retrieved from https://slate.com/business/2020/04/coronavirus-architecture-1918-flu-cholera-modernism.html.

Chen, P., Jiao, J. F., Xu, M. Y., Gao, X., & Bischak, C. (2018). Promoting active student travel: A longitudinal study. *Journal of Transport Geography, 70*, 265–274. https://doi.org/10.1016/j.jtrangeo.2018.06.015

Chen, P., Mao, L. J., Nassis, G. P., Harmer, P., Ainsworth, B. E., & Li, F. Z. (2020). Coronavirus disease (COVID-19): The need to maintain regular physical activity while taking precautions. *Journal of Sport and Health Science, 9*(2), 103–104. https://doi.org/10.1016/j.jshs.2020.02.001

Constandt, B., Thibaut, E., De Bosscher, V., Scheerder, J., Ricour, M., & Willem, A. (2020). Exercising in times of lockdown: An analysis of the impact of COVID-19 on levels and patterns of exercise among adults in Belgium. *International Journal of Environmental Research and Public Health, 17*(11). https://doi.org/10.3390/ijerph17114144

Coogan, P. F., White, L. F., Adler, T. J., Hathaway, K. M., Palmer, J. R., & Rosenberg, L. (2009). Prospective study of urban form and physical activity in the black women's health study. *American Journal of Epidemiology, 170*(9), 1105–1117. https://doi.org/10.1093/aje/kwp264

Craig, C. L., Marshall, A. L., Sjöström, M., Bauman, A. E., Booth, M. L., Ainsworth, B. E., … Oja, P. (2003). International physical activity questionnaire: 12-Country reliability and validity. *Medicine and Science in Sports and Exercise, 35*(8), 1381–1395. https://doi.org/10.1249/01.mss.0000078924.61453.fb

De Vos, J. (2020). The effect of COVID-19 and subsequent social distancing on travel behavior. *Transportation Research Interdisciplinary Perspectives, 5*, Article 100121. https://doi.org/10.1016/j.trip.2020.100121

Dejtiar, F. (2020). *Is coronavirus pandemic accelerating the digitalization and automation of cities?*. Retrieved from https://www.archdaily.com/936064/is-coronavirus-pandemic-accelerating-the-digitalization-and-automation-of-cities.

DiMaggio, C., Klein, M., Berry, C., & Frangos, S. (2020). Black/African American Communities are at highest risk of COVID-19: Spatial modeling of New York City ZIP Code–Level testing results. *Annals of Epidemiology, 51*, 7–13. https://doi.org/10.1016/j.annepidem.2020.08.012

Ding, D., & Gebel, K. (2012). Built environment, physical activity, and obesity: What have we learned from reviewing the literature? *Health & Place, 18*(1), 100–105. https://doi.org/10.1016/j.healthplace.2011.08.021

Eisenberg, Y., Vanderbom, K. A., & Vasudevan, V. (2017). Does the built environment moderate the relationship between having a disability and lower levels of physical activity? A systematic review. *Preventive Medicine, 95*, S75–S84. https://doi.org/10.1016/j.ypmed.2016.07.019

Ewing, R., & Cervero, R. (2010). Travel and the built environment. *Journal of the American Planning Association, 76*(3), 265–294. https://doi.org/10.1080/01944361003766766

Forsyth, A., Oakes, J. M., Schmitz, K. H., & Hearst, M. (2007). Does residential density increase walking and other physical activity? *Urban Studies, 44*(4), 679–697. https://doi.org/10.1080/00420980601184729

Giustino, V., Parroco, A. M., Gennaro, A., Musumeci, G., Palma, A., & Battaglia, G. (2020). Physical activity levels and related energy expenditure during COVID-19 quarantine among the sicilian active population: A cross-sectional online survey study. *Sustainability, 12*(11). https://doi.org/10.3390/su12114356

Gürdür Broo, D., Lamb, K., Ehwi, R. J., Pärn, E., Koronaki, A., Makri, C., … Zomer, T. (2021). Built environment of Britain in 2040: Scenarios and strategies. *Sustainable Cities and Society, 65*, Article 102645. https://doi.org/10.1016/j.scs.2020.102645

Handy, S. L., Boarnet, M. G., Ewing, R., & Killingsworth, R. E. (2002). How the built environment affects physical activity - Views from urban planning. *American Journal of Preventive Medicine, 23*(2), 64–73. https://doi.org/10.1016/s0749-3797(02)00475-0

Heo, S., Lim, C. C., & Bell, M. L. (2020). Relationships between Local Green Space and Human Mobility Patterns during COVID-19 for Maryland and California, USA. *Sustainability, 12*(22). https://doi.org/10.3390/su12229401

Hino, K., Usui, H., & Hanazato, M. (2020). Three-year longitudinal association between built environmental factors and decline in older adults' step count: Gaining insights for age-friendly urban planning and design. *International Journal of Environmental Research and Public Health, 17*(12). https://doi.org/10.3390/ijerph17124247

Hoehner, C. M., Ramirez, L. K. B., Elliott, M. B., Handy, S. L., & Brownson, R. C. (2005). Perceived and objective environmental measures and physical activity among urban adults. *American Journal of Preventive Medicine, 28*(2), 105–116. https://doi.org/10.1016/j.amepre.2004.10.023

Honey-Rosés, J., Anguelovski, I., Bohigas, J., Chireh, V., Daher, C., Konijnendijk van den Bosch, C., … Nieuwenhuijsen, M. (2020). *The impact of COVID-19 on public space: A review of the emerging questions*. Retrieved from. https://doi.org/10.31219/osf.io/rf7xa.

Huang, J., Kwan, M.-P., Kan, Z., Wong, M. S., Kwok, C. Y. T., & Yu, X. (2020). Investigating the relationship between the built environment and relative risk of COVID-19 in Hong Kong. *International Journal of Applied Earth Observation and Geoinformation : ITC Journal, 9*(11), 624.

Jeon, C. Y., Lokken, R. P., Hu, F. B., & Van Dam, R. M. (2007). Physical activity of moderate intensity and risk of type 2 diabetes: A systematic review. *Diabetes Care, 30*(3), 744–752.

Joh, K., Chakrabarti, S., Boarnet, M. G., & Woo, A. (2015). The Walking Renaissance: A Longitudinal Analysis of Walking Travel in the Greater Los Angeles Area, USA. *Sustainability, 7*(7), 8985–9011. https://doi.org/10.3390/su7078985

Jordan, R. E., Adab, P., & Cheng, K. K. (2020). Covid-19: Risk factors for severe disease and death. *Bmj-British Medical Journal, 368*. https://doi.org/10.1136/bmj.m1198

Klaus, I. (2020). *The post-pandemic urban future is already here*. Retrieved from. Citylab https://www.citylab.com/design/2020/04/coronavirus-urban-planning-cities-architecture-history/609262/.

Klompas, M., Baker, M. A., & Rhee, C. (2020). Airborne transmission of SARS-CoV-2 theoretical considerations and available evidence. *Jama-Journal of the American Medical Association, 324*(5), 441–442. https://doi.org/10.1001/jama.2020.12458

Kocak Tufan, Z., & Kayaaslan, B. (2020). Crushing the curve, the role of national and international institutions and policy makers in COVID-19 pandemic. *Turkish Journal of Medical Sciences, 50*, 495–508. https://doi.org/10.3906/sag-2004-167

Lesser, I. A., & Nienhuis, C. P. (2020). The impact of COVID-19 on physical activity behavior and well-being of canadians. *International Journal of Environmental Research and Public Health, 17*(11). https://doi.org/10.3390/ijerph17113899

Liu, J., Xiao, L., Yang, L., & Zhou, J. (2020). A tale of two social groups in Xiamen, China: Trip frequency of migrants and locals and its determinants. *Travel Behaviour and Society, 20*, 213–224.

Lu, Y., Xiao, Y., & Ye, Y. (2017). Urban density, diversity and design: Is more always better for walking? A study from Hong Kong. *Preventive Medicine, 103*, S99–S103. https://doi.org/10.1016/j.ypmed.2016.08.042

Lu, Y., Sun, G. B., Gou, Z. H., Liu, Y., & Zhang, X. L. (2019). A dose-response effect between built environment characteristics and transport walking for youths. *Journal of Transport & Health, 14*. https://doi.org/10.1016/j.jth.2019.100616

Lu, Y., Chen, L., Liu, X., Yang, Y., Sullivan, W. C., Xu, W., … Jiang, B. (2021). Green spaces mitigate racial disparity of health: A higher ratio of green spaces indicates a lower racial disparity in SARS-CoV-2 infection rates in the USA. *Environment International, 152*. https://doi.org/10.1016/j.envint.2021.106465

Luo, Z. H., O'Connor, P., & Enquist, P. (2016). City'S Choice. *Landscape Architecture Frontiers, 4*(2), 36–49.

Lu, Y., Zhao, J., Wu, X., & Lo, S. M. (2021). Escaping to nature during a pandemic: A natural experiment in Asian cities during the COVID-19 pandemic with big social media data. *Science of the Total Environment, 777*. https://doi.org/10.1016/j.scitotenv.2021.146092

Magill, M. (2011). Moderators and mediators in social work research: Toward a more ecologically valid evidence base for practice. *Journal of Social Work (London, England), 11*(4), 387–401. https://doi.org/10.1177/1468017310379930

McCormack, G. R., Giles-Corti, B., & Bulsara, M. (2008). The relationship between destination proximity, destination mix and physical activity behaviors. *Preventive Medicine, 46*(1), 33–40. https://doi.org/10.1016/j.ypmed.2007.01.013

McLaren, L., & Hawe, P. (2005). Ecological perspectives in health research. *Journal of Epidemiology and Community Health, 59*(1), 6–14. https://doi.org/10.1136/jech.2003.018044

Megahed, N. A., & Ghoneim, E. M. (2020). Antivirus-built environment: Lessons learned from Covid-19 pandemic. *Sustainable Cities and Society, 61*, Article 102350. https://doi.org/10.1016/j.scs.2020.102350

Mitchell, R., & Popham, F. (2008). Effect of exposure to natural environment on health inequalities: An observational population study. *Lancet, 372*(9650), 1655–1660. https://doi.org/10.1016/S0140-6736(08)61689-X

Mitra, R., Moore, S. A., Gillespie, M., Faulkner, G., Vanderloo, L. M., Chulak-Bozzer, T., … Tremblay, M. S. (2020). Healthy movement behaviours in children and youth during the COVID-19 pandemic: Exploring the role of the neighbourhood environment. *Health & Place, 65*. https://doi.org/10.1016/j.healthplace.2020.102418

Mora, S., Cook, N., Buring, J. E., Ridker, P. M., & Lee, I.-M. (2007). Physical activity and reduced risk of cardiovascular events: Potential mediating mechanisms. *Circulation, 116*(19), 2110.

Muggah, R., & Ermacora, T. (2020). *Opinion: Redesigning the COVID-19 city*. Retrieved from https://www.npr.org/2020/04/20/839418905/opinion-redesigning-the-covid-19-city.

Neto, L. O., Elsangedy, H. M., Tavares, V. D. O., Teixeira, C. V. L. S., Behm, D. G., & Silva-Grigoletto, M. E. D. (2020). #TrainingInHome - Training at home during the COVID-19 (SARS-COV2) pandemic: Physical exercise and behavior-based approach. *Brazilian Journal of Exercise Physiology, 19*, 4–14.

Nguyen, T. M. C., Kato, H., & Phan, L. B. (2020). Is built environment associated with travel mode choice in developing cities? Evidence from Hanoi. *Sustainability, 12*(14). https://doi.org/10.3390/su12145773

Nieuwenhuijsen, M. J. (2020). Urban and transport planning pathways to carbon neutral, liveable and healthy cities; A review of the current evidence. *Environment International, 140*. https://doi.org/10.1016/j.envint.2020.105661

O'Connor, P. J., Raglin, J. S., & Martinsen, E. W. (2000). Physical activity, anxiety and anxiety disorders. *International Journal of Sport Psychology, 31*(2), 136–155.

Penedo, F. J., & Dahn, J. R. (2005). Exercise and well-being: A review of mental and physical health benefits associated with physical activity. *Current Opinion in Psychiatry, 18*(2), 189–193.

Powell, K. E., King, A. C., Buchner, D. M., Campbell, W. W., DiPietro, L., Erickson, K. I., … Whitt-Glover, M. C. (2019). The scientific foundation for the physical activity guidelines for americans, 2nd edition. *Journal of Physical Activity & Health, 16*(1), 1–11. https://doi.org/10.1123/jpah.2018-0618

Qian, H., Miao, T., Liu, L., Zheng, X., Luo, D., & Li, Y. (2020). *Indoor transmission of SARS-CoV-2*. Retrieved from. https://doi.org/10.1101/2020.04.04.20053058 https://www.medrxiv.org/content/medrxiv/early/2020/04/07/2020.04.04.20053058.full.pdf.

Raj, V. A. A., Velraj, R., & Haghighat, F. (2020). The contribution of dry indoor built environment on the spread of Coronavirus: Data from various Indian states. *Sustainable Cities and Society, 62*. https://doi.org/10.1016/j.scs.2020.102371

Reiner, M., Niermann, C., Jekauc, D., & Woll, A. (2013). Long-term health benefits of physical activity–a systematic review of longitudinal studies. *BMC Public Health, 13*(1), 1–9.

Saelens, B. E., Sallis, J. F., Frank, L. D., Cain, K. L., Conway, T. L., Chapman, J. E., … Kerr, J. (2012). Neighborhood environment and psychosocial correlates of adults' physical activity. *Medicine and Science in Sports and Exercise, 44*(4), 637–646. https://doi.org/10.1249/MSS.0b013e318237fe18

Sallis, & Pratt, M. (2020). *A call to action: Physical activity and COVID-19*. Retrieved from https://www.exerciseismedicine.org/support_page.php/stories/?b=896.

Sallis, J. F., & Saelens, B. E. (2000). Assessment of physical activity by self-report: Status, limitations, and future directions (vol 71, pg 1, 2000). *Research Quarterly for Exercise and Sport, 71*(4), 409–409.

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

Sallis, J. F., Adlakha, D., Oyeyemi, A., & Salvo, D. (2020). An international physical activity and public health research agenda to inform coronavirus disease-2019

policies and practices. *Journal of Sport and Health Science, 9*(4), 328–334. https://doi.org/10.1016/j.jshs.2020.05.005

Sallis, J. F., Cerin, E., Conway, T. L., Adams, M. A., Frank, L. D., Pratt, M., … Owen, N. (2016). Physical activity in relation to urban environments in 14 cities worldwide: A cross-sectional study. *Lancet, 387*(10034), 2207–2217. https://doi.org/10.1016/S0140-6736(15)01284-2

Sekulic, D., Blazevic, M., Gilic, B., Kvesic, I., & Zenic, N. (2020). Prospective analysis of levels and correlates of physical activity during COVID-19 pandemic and imposed rules of social distancing; gender specific study among adolescents from Southern Croatia. *Sustainability, 12*(10). https://doi.org/10.3390/su12104072

Stier, A., Berman, M., & Bettencourt, L. (2020). *COVID-19 attack rate increases with city size Mansueto*. Inst. Urban Innov. Res. Pap.. Forthcom.

Stokols, D. (1996). Translating social ecological theory into guidelines for community health promotion. *American Journal of Health Promotion, 10*(4), 282–298. https://doi.org/10.4278/0890-1171-10.4.282

Ströhle, A. (2009). Physical activity, exercise, depression and anxiety disorders. *Journal of Neural Transmission, 116*(6), 777.

Sun, B. D., Ermagun, A., & Dan, B. (2017). Built environmental impacts on commuting mode choice and distance: Evidence from Shanghai. *Transportation Research Part D-Transport and Environment, 52*, 441–453. https://doi.org/10.1016/j.trd.2016.06.001

Sun, G. B., Oreskovic, N. M., & Lin, H. (2014). How do changes to the built environment influence walking behaviors? A longitudinal study within a university campus in Hong Kong. *International Journal of Health Geographics, 13*. https://doi.org/10.1186/1476-072x-13-28

Sun, C., & Zhai, Z. (2020). The efficacy of social distance and ventilation effectiveness in preventing COVID-19 transmission. *Sustainable Cities and Society, 62*, Article 102390. https://doi.org/10.1016/j.scs.2020.102390

Taylor, S. E., & Stanton, A. L. (2007). Coping resources, coping processes, and mental health. *Annual Review of Clinical Psychology, 3*, 377–401. https://doi.org/10.1146/annurev.clinpsy.3.022806.091520

Tewahade, S., Li, K. G., Goldstein, R. B., Haynie, D., Iannotti, R. J., & Simons-Morton, B. (2020). Association between the built environment and active transportation among US ADOLESCENTS. *Annals of Behavioral Medicine, 54*. S102-S102.

Tomey, K. (2005). Urban sprawl and public health: Designing, planning, and building for healthy communities. *Journal of Planning Literature, 19*(4), 458–459. https://doi.org/10.1177/0885412205275355

Van Cauwenberg, J., De Bourdeaudhuij, I., De Meester, F., Van Dyck, D., Salmon, J., Clarys, P., … Deforche, B. (2011). Relationship between the physical environment and physical activity in older adults: A systematic review. *Health & Place, 17*(2), 458–469. https://doi.org/10.1016/j.healthplace.2010.11.010

Venter, Z., Barton, D., Gundersen, V., Figari, H., & Nowell, M. (2020). Urban nature in a time of crisis: Recreational use of green space increases during the covid-19 outbreak in oslo, norway. *Environmental Research Letters*.

Warburton, D. E., Nicol, C. W., & Bredin, S. S. (2006). Health benefits of physical activity: The evidence. *Cmaj, 174*(6), 801–809.

World Health Organization. (2020a). *Coronavirus disease 2019 (COVID-19) situation Report-51*. Geneva, Switzerland: World Health Organization.

World Health Organization. (2020b). *Global recommendations on physical activity for health*. Geneva, Switzerland: World Health Organization.

World Health Organization. (2020c). *Novel coronavirus (2019-nCoV) situation Report-11*. Geneva, Switzerland: World Health Organization.

Wu, A. D., & Zumbo, B. D. (2007). Understanding and using mediators and moderators. *Social Indicators Research, 87*(3), 367. https://doi.org/10.1007/s11205-007-9143-1

Xie, J., Luo, S. X., Furuya, K., & Sun, D. J. (2020). Urban parks as green buffers during the COVID-19 pandemic. *Sustainability, 12*(17). https://doi.org/10.3390/su12176751

Yang, L., Griffin, S., Khaw, K. T., Wareham, N., & Panter, J. (2017). Longitudinal associations between built environment characteristics and changes in active commuting (vol 17, 458, 2017). *BMC Public Health, 17*. https://doi.org/10.1186/s12889-017-4843-1

Yang, Y., He, D., Gou, Z., Wang, R., Liu, Y., & Lu, Y. (2019). Association between street greenery and walking behavior in older adults in Hong Kong. *Sustainable Cities and Society, 51*, Article 101747. https://doi.org/10.1016/j.scs.2019.101747

Yang, L., Ao, Y., Ke, J., Lu, Y., & Liang, Y. (2021). To walk or not to walk? Examining non-linear effects of streetscape greenery on walking propensity of older adults. *Journal of Transport Geography, 94*, 103099.

Zhang, R. Y., Li, Y. X., Zhang, A. N. L., Wang, Y., & Molina, M. J. (2020). Identifying airborne transmission as the dominant route for the spread of COVID-19 (vol 117, pg 14857, 2020). *Proceedings of the National Academy of Sciences of the United States of America, 117*(41), 25942–25943. https://doi.org/10.1073/pnas.2018637117