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Research Letter

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Multiscale mobility explains differential associations between the gross domestic product and COVID-19 transmission in Chinese cities

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The rapid dissemination of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has caused a global pandemic of the novel coronavirus disease 2019 (COVID-19). Despite that early non-pharmaceutical interventions (NPIs) have contained or mitigated the initial spread of COVID-19 in a number of countries, resurgence of cases has been reported in the northern hemisphere entering the winter of 2020. Due to the recurrent and endemic potential of COVID-19 outbreaks,[1] understanding the risk factors associated with COVID-19 transmission is essential for preparedness and response.

Recent studies suggest that human mobility[2–6] and geographic components[7] are major risk factors driving the spatial spread of COVID-19. For instance, Jia *et al.*[2] and Tian *et al.*[3] both found that the cumulative number of confirmed cases was positively correlated with the cumulative number of passengers who travelled from the epicentre (i.e. Wuhan, Hubei province) to each other city in mainland China. Here, using granular human mobility data in mainland China, we quantify the association between COVID-19 transmission and an important socioeconomic factor, the gross domestic product (GDP), in 296 Chinese cities. In China, cities with higher GDP are generally more populated and urbanized. We hypothesize that the more frequent human interactions in urban settings could potentially increase the transmission risk of COVID-19.

The aforementioned seminal studies[2–7] mainly analysed the daily number of confirmed COVID-19 cases documented by health authorities. However, documented case count data can substantially underestimate the transmission risk and epidemic size due to underreporting and reporting delay.[8] To more accurately describe the COVID-19 transmission, we estimated the number of true incident cases (including both documented and undocumented cases) infected each day in each of the 296 Chinese cities before 8 February 2020. We conducted this estimation using a dynamic metapopulation model that accounts for unreported cases and adjusts for the lag from infection acquisition to confirmation (see Supplementary Information available as Supplementary data at *JTM* online).[8]

We computed the correlation between the GDP in 2018[2] and estimated cumulative infections over time (Figure 1A, Table 1). A weak but stable positive correlation is observed across the whole study period, which agrees with our hypothesis. However, a simple stratification of all 296 cities according to whether a city is located within the Hubei province unravels a much higher positive correlation for cities outside the Hubei province and a moderate negative correlation for cities within the Hubei province. Such a clear disparity in the city-stratified associations between GDP and COVID-19 transmission is reminiscent of the Simpson's paradox (i.e. distinct associations in certain subgroups disappear when subgroups are merged together).[9] Differential associations between GDP and the cumulative confirmed cases were also observed in Chinese cities stratified by location (Figure S1 available as Supplementary data at *JTM* online). Similar patterns remained between the cumulative infections per 10 000 people and GPD per capita (Figures S2 and S3 available as Supplementary data at *JTM* online) as well as other three socioeconomic indictors for wealth and well-being, including the average wage of employed staff and workers, public finance expenditure per capita and household saving deposits at year-end per capita (Figure S4 available as Supplementary data at *JTM* online).

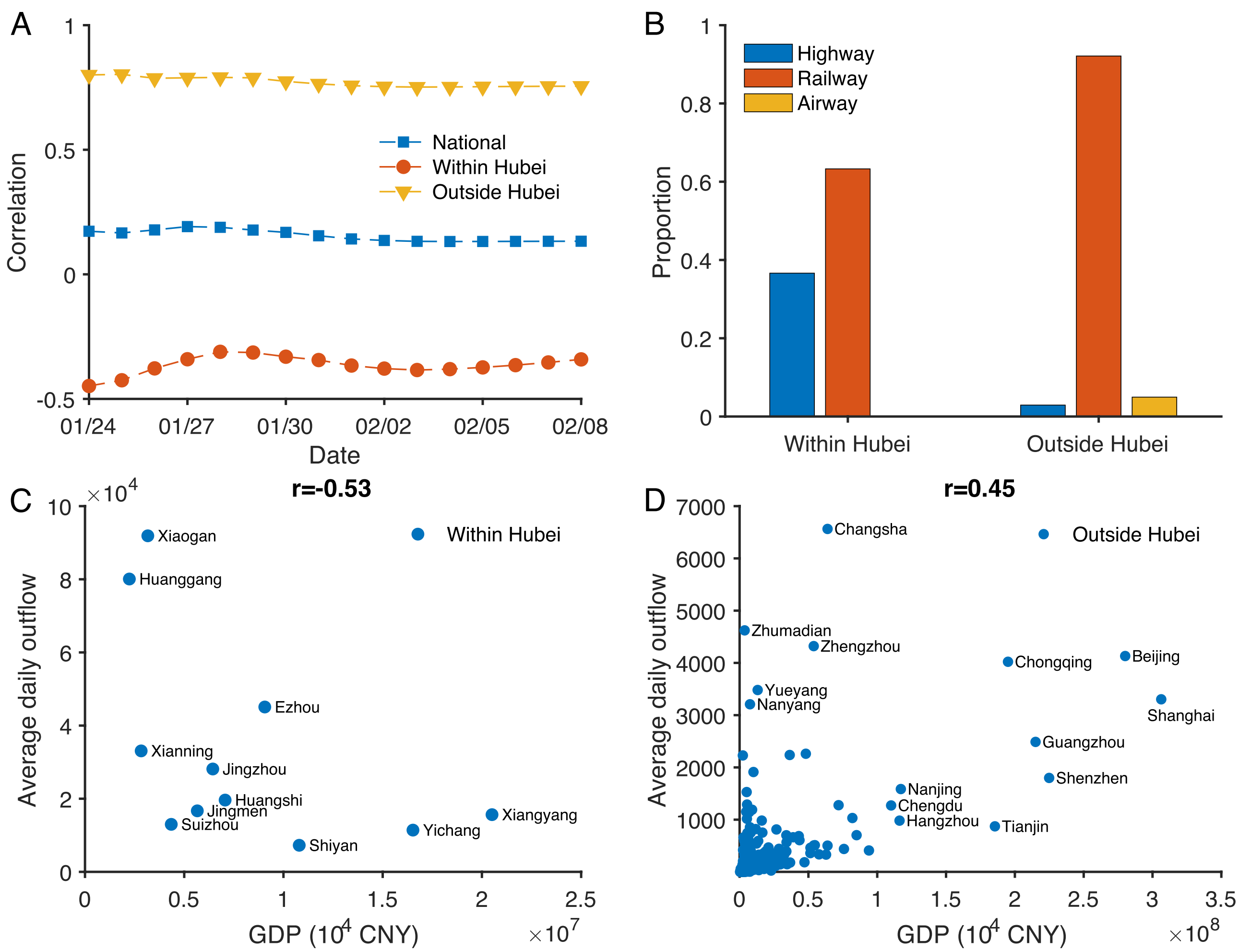

Figure 1. (A) Pearson correlation between the estimated cumulative infections on each day from 24 January to 8 February 2020 and the GDP of cities within the Hubei province (blue square), outside Hubei province (red circle) and all 296 cities (yellow triangular). (B) Proportion of highway (blue bar), railway (red bar) and airway (yellow bar) travels among population outflow leaving from Wuhan to cities within (left) and outside (right) Hubei province. The short-range inter-city movements within the Hubei province were mainly transported via railway (63.3%) and highway (36.6%), with negligible airway transportation (<0.1%). In contrast, the long-range movements from Wuhan to cities in other provinces were dominated by the railway transportation (92.1%), with airway and highway accounting for 5.0% and 2.9% total travels, respectively. (C) Relationship between GDP and the average daily outflow from Wuhan to 11 cities within Hubei province between 1 January and 24 January 2020 (Pearson correlation coefficient, $r = -0.53$). (D) Relationship between GDP and the average daily outflow from Wuhan to 285 cities outside Hubei province (Pearson correlation coefficient, $r = 0.45$).

We find that the distinct association between GDP and COVID-19 transmission can be explained by the multiscale mobility from Wuhan to other cities. Before Wuhan's lockdown on 23 January 2020, transportation of several billion trips during the Spring Festival season (i.e. 'chunyun') significantly accelerated the spatial spread of COVID-19 throughout China.[3,4,7] Using Baidu mobile phone data between 1 January and 24 January 2020, we found that 75.7% of travellers leaving from Wuhan moved to cities within the Hubei province through short-range travels. We then used data from Tencent during 'chunyun' in 2018 to estimate the proportion of travellers transported via highway, railway and airway (Figure 1B). The within- and cross-province travels from Wuhan exhibit a dramatic difference in the mode of transport.

We observed different mobility patterns for short-range and long-range travels originating from Wuhan. As a regional economic centre, Wuhan attracts a large number of migrant workers and new dwellers from nearby cities in the Hubei province. To celebrate Spring Festival, many of them returned their birthplaces to visit the original family, travelling mainly by railway and highway. For cities within the Hubei province, we found a negative correlation between the GDP and daily average population outflow from Wuhan (Figure 1C), which reflects that people from less-urbanized cities in the Hubei province tend to migrate to Wuhan for seeking jobs or for attending schools. Within the Hubei province, Wuhan is strongly connected with the regional cities with lower GDP via short-range mobility during the 'chunyun' period. For cities outside the Hubei province, we found a positive correlation between the GDP and daily average population outflow from Wuhan (Figure 1D). Due to close economic ties and the hub-and-spoke structure of railway and flight networks, Wuhan is also strongly connected with other economic centres outside the Hubei province via long-range railway and air travel. Given that the spatial spread of COVID-19 was largely

Table 1. Pearson correlation between the estimated cumulative infections on each day from 24 January to 8 February 2020 and the GDP of cities within the Hubei province, outside the Hubei province and all 296 cities

Date	National	Within Hubei	Outside Hubei
24-Jan	0.17	-0.45	0.80
25-Jan	0.17	-0.43	0.80
26-Jan	0.18	-0.38	0.79
27-Jan	0.19	-0.34	0.79
28-Jan	0.19	-0.31	0.79
29-Jan	0.18	-0.31	0.79
30-Jan	0.17	-0.33	0.77
31-Jan	0.15	-0.34	0.76
1-Feb	0.14	-0.37	0.76
2-Feb	0.14	-0.38	0.75
3-Feb	0.13	-0.38	0.75
4-Feb	0.13	-0.38	0.75
5-Feb	0.13	-0.37	0.75
6-Feb	0.13	-0.36	0.75
7-Feb	0.13	-0.35	0.75
8-Feb	0.13	-0.34	0.76

driven by the population outflows leaving from Wuhan during the 'chunyun' period,[2] we expect that more infections occurred in low-GDP cities within the Hubei province and in high-GDP cities outside the Hubei province. The stable correlation between the GDP and cumulative infections for cities outside the Hubei province indicates the success of NPIs to contain subsequent transmission from high-GDP cities to low-GDP cities in other provinces.[3,5]

The impact of multiscale mobility on the spatial spread of infectious diseases has been explored in previous mathematical modelling studies.[10] Numerical simulations of 2009 A/H1N1 pandemic influenza have suggested that the disease first rapidly spread from the Greater Mexico City to most hub populations of economic centres around the globe via long-range airline travels. Once a hub population established local transmission, the disease infected the surrounding areas via short-range ground travels. Here, we provide a real-world case study of COVID-19 to demonstrate that the structure and properties of multiscale mobility could shape the spatial transmission dynamics of SARS-CoV-2. As such, bulk analysis mixing up multiple geographical scales may lead to contradicting conclusions when evaluating the associations between the COVID-19 transmission and socioeconomic factors that differ for short-range and long-range mobility (e.g. urbanization). Similar issues may also occur during the early phase of an outbreak of an emerging infectious disease. A clear understanding of the mechanism underlying such differential patterns will be useful to the strategic response and planning against COVID-19.

Supplementary data

Supplementary data are available at *JTM* online.

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Conflict of interest

None declared.

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