



OPEN ACCESS

# Geo-social gradients in predicted COVID-19 prevalence in Great Britain: results from 1 960 242 users of the COVID-19 Symptoms Study app

Ruth C E Bowyer,<sup>1</sup> Thomas Varsavsky,<sup>2</sup> Ellen J Thompson,<sup>1</sup> Carole H Sudre,<sup>2,3</sup> Benjamin A K Murray,<sup>2</sup> Maxim B Freidin,<sup>1</sup> Darioush Yarand,<sup>1</sup> Sajaysurya Ganesh,<sup>4</sup> Joan Capdevila,<sup>4</sup> Elco Bakker,<sup>4</sup> M Jorge Cardoso,<sup>2</sup> Richard Davies ,<sup>4</sup> Jonathan Wolf,<sup>4</sup> Tim D Spector,<sup>1</sup> Sebastien Ourselin,<sup>2</sup> Claire J Steves,<sup>1</sup> Cristina Menni <sup>1</sup>

► Additional material is published online only. To view please visit the journal online (<http://dx.doi.org/10.1136/thoraxjnl-2020-215119>).

<sup>1</sup>Twin Research, King's College London, London, UK

<sup>2</sup>School of Biomedical Engineering & Imaging Sciences, King's College London, London, UK

<sup>3</sup>MRC Unit for Lifelong Health and Ageing, University College London, London, UK

<sup>4</sup>Zoe Global Limited, London, UK

## Correspondence to

Dr Cristina Menni, Twin Research, King's College London, London, UK; [cristina.menni@kcl.ac.uk](mailto:cristina.menni@kcl.ac.uk)

RCEB and TV contributed equally.  
CJS and CM contributed equally.

Received 24 April 2020  
Revised 23 November 2020  
Accepted 24 November 2020  
Published Online First  
29 December 2020



► <http://dx.doi.org/10.1136/thoraxjnl-2020-216422>  
► <http://dx.doi.org/10.1136/thoraxjnl-2020-216673>



© Author(s) (or their employer(s)) 2021. Re-use permitted under CC BY. Published by BMJ.

**To cite:** Bowyer RCE, Varsavsky T, Thompson EJ, et al. *Thorax* 2021;**76**:723–725.

## ABSTRACT

Understanding the geographical distribution of COVID-19 through the general population is key to the provision of adequate healthcare services. Using self-reported data from 1 960 242 unique users in Great Britain (GB) of the *COVID-19 Symptom Study app*, we estimated that, concurrent to the GB government sanctioning lockdown, COVID-19 was distributed across GB, with evidence of 'urban hotspots'. We found a geo-social gradient associated with predicted disease prevalence suggesting urban areas and areas of higher deprivation are most affected. Our results demonstrate use of self-reported symptoms data to provide focus on geographical areas with identified risk factors.

The COVID-19 epidemic has led to large-scale closures and lockdown measures worldwide with the British government sanctioning lockdown from 23 March 2020 (<https://www.gov.uk/government/speeches/pm-address-to-the-nation-on-coronavirus-23-march-2020>).

Early in the pandemic, case distribution was not evenly spread across countries, with dense urban centres being the most affected.<sup>1</sup> Individuals in deprived areas have lower life expectancy,<sup>2</sup> are more likely to have multiple underlying comorbidities, have a higher level of influenza-associated hospitalisation<sup>3</sup> and therefore could be more susceptible to COVID-19.<sup>2</sup>

Based on the known socioeconomic health gradient, we hypothesised that individuals in deprived areas were at greater risk of contracting COVID-19. Understanding the geographical distribution of the virus in a socioeconomic context is key to assist adequate healthcare resourcing, particularly intensive care beds.<sup>4</sup>

Here we investigated the geographical distribution of COVID-19 in Great Britain (GB) and its association with area-level deprivation using self-reported data from almost 2 million users of the *COVID-19 Symptom Study*.<sup>5</sup>

We studied 1 960 242 unique GB app users (20–69 years old) reporting on COVID-19 symptoms, hospitalisation, reverse-transcription PCR (RT-PCR) test outcomes, demographic information and pre-existing medical conditions (online supplemental methods) over 23 days (29 March–19 April) of major social distancing measures ('lockdown').

We computed a proxy of contracting COVID-19, based on reported symptoms<sup>6</sup> (positive predicted value=0.69 (0.66; 0.71) (online supplemental methods). We then calculated a predicted prevalence as the proportion of app users that we predicted to have COVID-19 within each area (online supplementary figure S1).

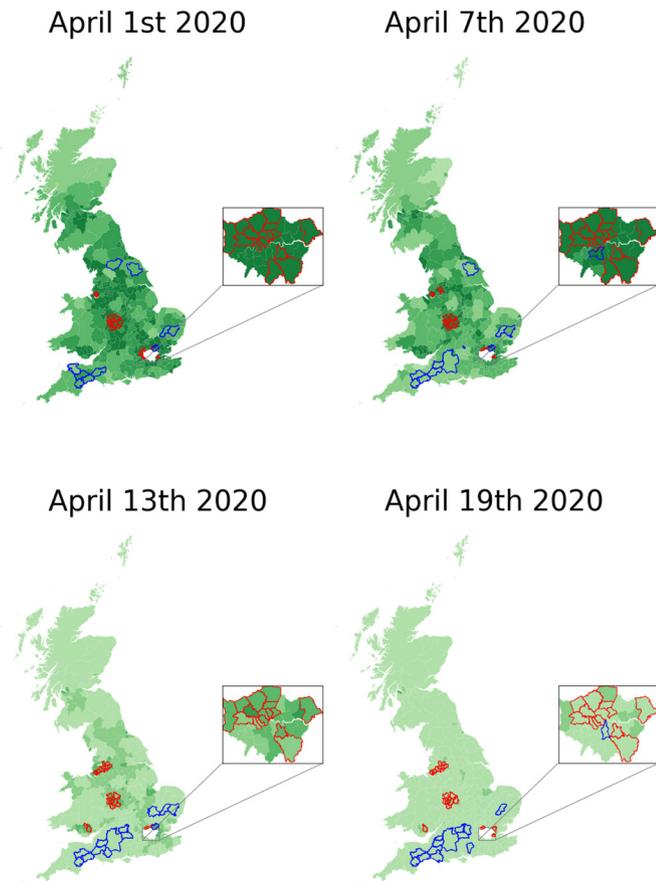
Following aggregation of variables to local authority district level (LAD/geographic unit representing ~17 000 individuals), we tested the geographical distribution of predicted prevalence at eight different time points spanning 23 days. We used Local Moran's I tests, which assess for non-random spatial distribution and clustering of a feature and can be used to identify disease hotspots and cold spots relative to the mean GB predicted prevalence<sup>7</sup> (online supplemental methods).

Next, we used data from the eight different time points and used multivariable mixed-effects models to investigate the association of predicted area-level prevalence (at middle super output area level (MSOA)) and deprivation (as captured by the Index of Multiple Deprivation) adjusting for different factors including geo-social mediators and confounders (air pollution, general practitioners per MSOA, household density and urbanicity) area level aggregates of obesity and comorbidities) and area-level adjusted mean age and sex and spatial autocorrelations<sup>8</sup> (online supplemental methods).

table [table 1](#) and online supplemental table S1. The number of predicted COVID-19 positive individuals ranged between 15 991 and 79 378.

Local Moran's I showed that predicted COVID-19 prevalence clustered in urban areas across GB when considered as a proportion of the population per LAD<sup>7</sup> ([figure 1](#) and online supplemental figure S2) adjusting for multiple testing. Predicted prevalence decreased over time, consistent with 'lockdown' ([figure 1](#) and online supplemental figure S2) (pairwise Wilcoxon rank-sum tests, prevalence: all time points except T2:T3 and T1:T4,  $p<0.001$ ), but some hotspots remained.

In the MSOA-level analysis, area-level deprivation was significantly associated with predicted area-level prevalence in all models (M1–M6, see online supplemental table S2), including in the full model (M6) when adjusting for all geo-social covariates and comorbidities (M6: Beta (95% CI) = -0.15



**Figure 1** Geographical distribution of predicted COVID-19 prevalence across four time points. Prevalence is presented as proportional to the responders per local authority district (LAD). Analyses are adjusted for multiple testing using Benjamini-Hochberg false discovery rate correction ( $p < 0.05$ ). Inset highlights London where LAD areas are smaller. Hot and cold spots are defined relatively to their neighbours and the mean GB predicted prevalence. Red/blue coloured perimeter lines around each LAD denote hotspot/coldspot.

( $-0.17$  to  $-0.130$ ,  $p < 0.001$ ). This suggests that people in deprived areas were at higher risk.

Predicted COVID-19 prevalence was higher in urban areas compared with rural and in more deprived areas compared with less deprived. This could reflect the likelihood of individuals in more deprived areas working/living with people whose vocations mean they are unable to work from home and are thus more likely to be exposed to circulating COVID-19. Accumulation of socioenvironmental exposures across the life course are known to contribute to a greater health deficit and disease burden<sup>2</sup>; our results suggest that COVID-19 is no exception.

Moreover, our study illustrates how app data could be used to successfully monitor COVID-19 over time and identify hotspots as the viral pandemic progresses and social distancing measures are implemented or eased. Using this method, we detected a geo-social gradient associated with prevalence in the context of COVID-19, suggesting the focus of resources should be on deprived urban areas.

Our study has some limitations and assumptions. We used self-reported data on symptoms that can lead to bias. For example, should users in deprived areas report more symptoms due to a facet of the socioeconomic environment (eg, higher air pollution), this could lead to an incorrectly higher predicted prevalence in deprived areas. Second, app users are a self-selected group, not representative of the general population. Our approach to adjust for age and sex differences at MSA level is unlikely to sufficiently overcome selection and collider bias.<sup>9</sup> Third, our predicted COVID-19 prevalence is not from confirmed tests via RT-PCR, but rather based on self-reported symptoms. Additionally, we assume that people who have symptoms or have been exposed to COVID-19 are equally likely to use the app as those who do not. We performed a sensitivity analysis by rerunning the pooled analysis on individuals who were self-reportedly healthy at sign up and found the observed associations remained (online supplemental table S3), suggesting selection bias associated with being unhealthy at sign up is not influencing the observed associations of COVID-19 and deprivation. We also assume that people report symptoms in the same way and that their drop-out patterns do not differ by space, time and symptom reports. Finally, we aggregated data at MSA level

**Table 1** Demographic characteristics of the study population at eight time points

	29 March 2020	1 April 2020	4 April 2020	7 April 2020	10 April 2020	13 April 2020	16 April 2020	19 April 2020	All unique users
N	1 324 843	1 431 515	1 142 923	1 083 601	995 157	985 860	980 608	1 164 262	1 960 242
Predicted COVID-19 (n/%)	60 827 (4.6)	79 378 (5.6)	62 508 (5.5)	48 418 (4.5)	30 132 (3.0)	22 352 (2.3)	16 586 (1.7)	15 991 (1.4)	117 614 (6.0)
Average number of reports per user	2.9	3.8	4.2	4.7	5	5	5	4.5	4.4
Age, years (median (IQR))	41 (21)	41 (21)	43 (21)	44 (22)	45 (21)	45 (21)	46 (21)	45 (21)	42.2 (21.8)
Male, (n/%)	426 923 (32.2)	459 620 (32.1)	365 078 (31.9)	353 233 (32.6)	327 608 (32.9)	327 620 (33.3)	327 114 (33.3)	388 378 (33.4)	654 950 (33.4)
Obesity, %	21.3	21.4	20.7	20.3	21.6	22.1	21.4	21.7	21.5
Kidney disease, %	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.5
Lung disease, %	12.2	12.3	12.5	12.5	12.4	12.4	12.4	12.4	12.2
Diabetes, %	2.4	2.5	2.7	2.7	2.8	2.9	2.9	2.9	2.4
Smokers, %	10.5	10.5	9.7	9.4	9.0	8.8	8.7	9.0	10.4
Heartdisease, %	1.4	1.4	1.6	1.6	1.7	1.7	1.7	1.7	1.4

Obesity: BMI  $\geq 30$  kg/m<sup>2</sup>.

At each time point, we only include users who have made an assessment in the previous 7 days. Exclusion criteria are listed in the supplements. Users are asked daily whether (or not) they have any symptoms. Predicted COVID-19 was calculated on users who reported on symptoms. Users who reported having no symptoms were included in the area-level predicted prevalence estimates (please see the supplements for details). BMI, body mass index.

that could lead to ecological bias. We also cannot conclude that deprivation increased COVID-19 prevalence, as there could be unmeasured confounders or other factors.

Future work should check our assumptions and seek to integrate these data with data on area-level morbidity, extended pollution data, ethnicity and disease severity. Indeed, higher mortality has been observed among minority ethnic groups,<sup>10</sup> and disentangling the environmental and biological factors contributing to greater disease burden in both deprived areas and among ethnic minorities is an essential focus of future work to ensure resources and intervention are better assigned.

**Twitter** M Jorge Cardoso @mjorgecardoso

**Acknowledgements** We express our sincere thanks to all the participants of the COVID Symptom Study app. We would like to thank the staff of Zoe Global Limited, the Department of Twin Research for their tireless work in contributing to the running of the study and data collection. Finally, we would like to thank Professor Kate Tilling of the University of Bristol for her invaluable insight and help in refining the manuscript.

**Contributors** Conceived and designed the experiments: CJS, TDS, SO and CM; analysed the data: RCB and TV. Contributed reagents/materials/analysis tools: MF, CHS, BM, MF, DY, SG, JC, ET, EB, MJC, RD and JW wrote the manuscript: RCB, TV and CM; revised the manuscript: all.

**Funding** Zoe provided in kind support for all aspects of building, running and supporting the app and service to all users worldwide. The Department of Twin Research is funded by the Wellcome Trust, Medical Research Council, European Union, Chronic Disease Research Foundation (CDRF), Zoe Global Ltd and the National Institute for Health Research (NIHR)-funded BioResource, Clinical Research Facility and Biomedical Research Centre based at Guy's and St Thomas' NHS Foundation Trust in partnership with King's College London. CM is funded by the Chronic Disease Research Foundation and by the MRC Aim-Hy project grant. CHS is an Alzheimer's Society Junior Fellowship AS-JF-17-011; SO and MJC are funded by the Wellcome/EPSCRC Centre for Medical Engineering (WT203148/Z/16/Z), Wellcome Flagship Programme (WT213038/Z/18/Z).

**Map disclaimer** The depiction of boundaries on this map does not imply the expression of any opinion whatsoever on the part of BMJ (or any member of its group) concerning the legal status of any country, territory, jurisdiction or area or of its authorities. This map is provided without any warranty of any kind, either express or implied.

**Competing interests** TDS is a consultant to Zoe Global Ltd ('Zoe'). SG, JC, EB, RD and JW are or have been employees of Zoe Global Limited. Other authors have no conflict of interest to declare.

**Patient consent for publication** Not required.

**Ethics approval** The Ethics for the app has been approved by King's College London ethics Committee (REMAS ID 18210, review reference LRS-19/20-18210), and all users provided consent for non-commercial use. An informal consultation with TwinsUK members over email and social media prior to the app having been launched found that they were overwhelmingly supportive of the project.

**Provenance and peer review** Not commissioned; externally peer reviewed.

**Open access** This is an open access article distributed in accordance with the Creative Commons Attribution 4.0 Unported (CC BY 4.0) license, which permits others to copy, redistribute, remix, transform and build upon this work for any purpose, provided the original work is properly cited, a link to the licence is given, and indication of whether changes were made. See: <https://creativecommons.org/licenses/by/4.0/>.

#### ORCID iDs

Richard Davies <http://orcid.org/0000-0003-2050-3994>  
Cristina Menni <http://orcid.org/0000-0001-9790-0571>

#### REFERENCES

- 1 Stier A, Berman M, Bettencourt L. COVID-19 attack rate increases with City size, 2020. Available: [https://paperssrn.com/sol3/paperscfm?abstract\\_id=3564464](https://paperssrn.com/sol3/paperscfm?abstract_id=3564464)
- 2 Marmot M. Health equity in England: the Marmot review 10 years on. *BMJ* 2020;368:m693.
- 3 Hungerford D, Ibarz-Pavon A, Cleary P, et al. Influenza-Associated hospitalisation, vaccine uptake and socioeconomic deprivation in an English City region: an ecological study. *BMJ Open* 2018;8:e023275.
- 4 Blumenshine P, Reingold A, Egarter S, et al. Pandemic influenza planning in the United States from a health disparities perspective. *Emerg Infect Dis* 2008;14:709–15.
- 5 Drew DA, Nguyen LH, Steves CJ, et al. Rapid implementation of mobile technology for real-time epidemiology of COVID-19. *Science* 2020;368:1362–7.
- 6 Menni C, Valdes AM, Freidin MB, et al. Real-Time tracking of self-reported symptoms to predict potential COVID-19. *Nat Med* 2020;26:1037–40.
- 7 Zhang C, Luo L, Xu W, et al. Use of local Moran's I and GIS to identify pollution hotspots of Pb in urban soils of Galway, Ireland. *Sci Total Environ* 2008;398:212–21.
- 8 Anselin L, Griffith DA. Do spatial effects really matter in regression analysis? *Papers - Regional Science Association* 1988.
- 9 Griffith GJ, Morris TT, Tudball MJ, et al. Collider bias undermines our understanding of COVID-19 disease risk and severity. *Nat Commun* 2020;11:5749.
- 10 Khunti K, Singh AK, Pareek M, et al. Is ethnicity linked to incidence or outcomes of covid-19? *BMJ* 2020;369:m1548.