Research Paper

Race, ethnicity, community-level socioeconomic factors, and risk of COVID-19 in the United States and the United Kingdom

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A B S T R A C T

Background: There is limited prior investigation of the combined influence of personal and community-level socioeconomic factors on racial/ethnic disparities in individual risk of coronavirus disease 2019 (COVID-19).

Methods: We performed a cross-sectional analysis nested within a prospective cohort of 2,102,364 participants from March 29, 2020 in the United States (US) and March 24, 2020 in the United Kingdom (UK) through December 02, 2020 via the COVID Symptom Study smartphone application. We examined the contribution of community-level deprivation using the Neighborhood Deprivation Index (NDI) and the Index of Multiple Deprivation (IMD) to observe racial/ethnic disparities in COVID-19 incidence. ClinicalTrials.gov registration: NCT04331509.

Findings: Compared with non-Hispanic White participants, the risk for a positive COVID-19 test was increased in the US for non-Hispanic Black (multivariable-adjusted odds ratio [OR], 1.32; 95% confidence interval [CI], 1.18–1.47) and Hispanic participants (OR, 1.42; 95% CI, 1.33–1.52) and in the UK for Black (OR, 1.17; 95% CI, 1.02–1.34), South Asian (OR, 1.39; 95% CI, 1.30–1.49), and Middle Eastern participants (OR, 1.38; 95% CI, 1.18–1.61). This elevated risk was associated with living in more deprived communities according to the NDI/IMD. After accounting for downstream mediators of COVID-19 risk, community-level
rates of SARS-CoV-2 infection, hospitalization, and death [1]. These affected by coronavirus disease 2019 (COVID-19), resulting in higher

1. Introduction

Racial and ethnic minorities have disproportionately high rates of SARS-CoV-2 infection, hospitalization, and death related to coronavirus disease 2019 (COVID-19). Prior studies, largely in the US, have examined the association between race/ethnicity and COVID-19 infection. However, these studies have not been able to jointly investigate personal risk factors in the context of community-level socioeconomic risk factors across countries.

2. Methods

2.1. Real-time assessment of COVID-19 using smartphone technology

We conducted a cross-sectional analysis nested within a prospective cohort of 2,102,364 participants who reported race and ethnicity through the COVID Symptom Study smartphone application since March 29, 2020 in the US and March 24, 2020 in the UK through December 02, 2020 [14]. The app was developed by Zoe Ltd. IT (London, UK) in collaboration with Massachusetts General Hospital (Boston, Massachusetts, USA) and King’s College London (London, UK). It offered users a guided interface to report baseline demographic information and comorbidities. Users were prompted to use the application daily to allow for longitudinal, prospective collection of concomitant symptoms, health care visits, and COVID-19 test results. Study participants were recruited through general media and social media outreach, as well as direct invitations from the investigators of long-running prospective cohorts [15]. At enrollment, participants provided electronic informed consent to the use of aggregated information for research purposes and agreed to applicable privacy policies and terms of use. For the current study, participants were followed up for the duration for which they used the app (median: 17 days). This research study was approved by the Partners Human Research Committee (Protocol 2020P00909) and King’s College London Ethics Committee (REMAS ID 18210, LRS-19/20-18210). The COVID Symptom Study app is registered with ClinicalTrials.gov, NCT04331509. C-HL, LHN, DAD, and ATC had full access to all the data in the study.

2.2. Assessment of risk factors, symptoms, and testing for COVID-19

Information collected through the application has previously been described [14]. Briefly, at enrollment, participants were asked to provide information on demographic factors and suspected risk factors for COVID-19 (Table 1 and 2). On first use and daily, participants were asked if they felt physically normal, and if not, what symptoms they were experiencing. They were also asked daily if they had been tested for COVID-19 and the results (none, negative, pending,
positive). To validate our case ascertainment, a subset of individuals who had reported symptoms in the COVID Symptom Study application were invited to provide a copy of the test results. Among 235 participants, we found that self-reported COVID-19 testing yielded a positive predictive value of 77% and a negative predictive value of 97% for confirmed medical record results. Although this was not examined by individual strata, given the simple in-app guidance and the uniform access to the app by our study participants, we did not expect case ascertainment by self-report to vary greatly by race and ethnicity. On first use of the app, participants also reported whether they had ever been exposed to someone with presumed or confirmed COVID-19 infection (such as co-workers, family members, or others). This variable served as an indicator of individual-level exposure to SARS-CoV-2 and had subtle inferences about the socioeconomic environment in which an individual resided.

2.3. Assessment of race and ethnicity

Individuals were asked to report with which race and/or ethnicity they self-identified. Questions were based on standard categories from the National Institutes of Health (race: White, Black, Asian, Native Hawaiian or other Pacific Islander, American Indian or Alaska Native, other, prefer not to say; ethnicity: Hispanic, non-Hispanic) [16] and the Office for National Statistics (White, Black, South Asian, Middle Eastern, Chinese, White and Black, mixed race, other, prefer not to say) [17] (Supplementary Table 1). Individuals who identified their race or ethnicity as “other” were provided an option to enter a free-text description. Those who identified as “Mixed Race” or selected more than one race were described as “more than one race” and grouped with “other race”. In the US, “Hispanic” was defined as any race of Hispanic or Latino ancestry. Other racial categories were defined as each respective race not of Hispanic or Latino ancestry (e.g., non-Hispanic White, non-Hispanic Black). Due to limited sample sizes, “Native Hawaiian or other Pacific Islander” and “American Indian or Alaskan Native” were grouped into “More than one/other race”. In the UK, individuals were asked to identify as “Chinese” or “South Asian”, where provided examples included “Indian, Pakistani, Bangladeshi, other”, but were not specifically asked about other racial identities from Asia. East/Southeast Asian countries such as Japan, the Philippines, and Thailand were the most common “other” free-text responses and were included as “East/Southeast Asian” if they had not previously identified as an existing category.

We excluded participants who did not provide information on racial or ethnic identity or selected “prefer not to say”. Country-specific percentages of racial groups in the study are provided in Supplementary Table 1 along with those in the general population as estimated by the US Census Bureau Population Estimates Program (2019) [18] and the England and Wales 2011 Census by the Office for National Statistics [19].

2.4. Assessment of community-level sociodemographic characteristics in the US

Socioeconomic variables at the ZIP Code Tabulation Area (ZCTA) level were collected from the US Census Bureau’s 2014–2018 American Community Survey [20]. Percentage of essential workers was calculated as the proportion of individuals employed in 14 major occupational categories, including “healthcare practitioners and
Table 2
Characteristics of study participants according to race and ethnicity in the United Kingdom.

| Variablesa | White | Black | South Asian | Middle Eastern | Chinese | East/Southeast Asian | More than one/other race |
|------------|-------|-------|-------------|---------------|--------|----------------------|-------------------------|
| No. participants | 1736547 | 10949 | 37638 | 6828 | 5762 | 1713 | 44139 |
| Age, years, median [IQR] | 48.0 [31.0, 61.0] | 44.0 [31.0, 55.0] | 41.0 [30.0, 52.0] | 41.0 [30.0, 55.0] | 40.0 [28.8, 51.0] | 44.0 [35.0, 53.0] | 31.0 [15.0, 48.0] |
| < 25, % | 17.6 | 16.5 | 18.6 | 16.2 | 18.3 | 10.0 | 40.5 |
| 25–34, % | 11.4 | 14.5 | 15.7 | 16.9 | 18.3 | 14.1 | 14.3 |
| 35–44, % | 14.8 | 19.6 | 23.2 | 24.2 | 24.6 | 27.2 | 15.3 |
| 45–54, % | 18.7 | 23.7 | 19.6 | 17.6 | 18.8 | 27.7 | 13.3 |
| 55–64, % | 18.6 | 19.1 | 11.4 | 13.3 | 10.8 | 12.3 | 9.9 |
| ≥ 65, % | 18.6 | 6.6 | 9.5 | 11.7 | 9.3 | 8.6 | 6.7 |
| Male sex, % | 44.0 | 49.4 | 42.9 | 54.0 | 38.8 | 28.4 | 44.7 |
| Body mass index, kg/m², median [IQR] | 25.3 [22.1, 29.3] | 26.9 [23.1, 31.3] | 24.6 [21.5, 28.0] | 25.3 [22.2, 29.1] | 22.5 [20.2, 25.4] | 23.1 [20.5, 26.2] | 23.5 [19.7, 27.9] |
| < 18.5, % | 8.5 | 8.1 | 9.8 | 7.1 | 12.1 | 9.1 | 19.3 |
| 18.5–24.9, % | 39.6 | 29.4 | 44.6 | 41.2 | 60.6 | 58.3 | 40.8 |
| 25–29.9, % | 30.1 | 31.2 | 29.4 | 31.0 | 19.6 | 23.6 | 21.9 |
| ≥ 30, % | 21.8 | 31.3 | 16.1 | 20.8 | 7.7 | 8.9 | 18.0 |
| Comorbidities, % | | | | | | | |
| Diabetes | 3.0 | 6.0 | 6.2 | 4.3 | 2.4 | 3.1 | 2.2 |
| Heart disease | 3.3 | 2.4 | 3.5 | 3.8 | 1.8 | 1.9 | 1.9 |
| Lung disease or asthma | 8.6 | 9.1 | 7.9 | 6.6 | 5.7 | 6.2 | 8.7 |
| Kidney disease | 0.8 | 1.3 | 1.0 | 1.1 | 0.7 | 0.2 | 0.7 |
| Cancer (active or in the past) | 1.4 | 1.2 | 0.8 | 1.1 | 0.7 | 1.2 | 0.8 |
| Pregnan=========

ty (females only), % | 0.6 | 0.7 | 1.0 | 0.8 | 0.8 | 0.8 | 0.7 |
| Medication usage, % | | | | | | | |
| Immunosuppressants | 3.6 | 4.1 | 3.5 | 3.0 | 2.3 | 2.5 | 3.1 |
| Chemo/Immunotherapy | 0.3 | 0.3 | 0.2 | 0.2 | 0.0 | 0.4 | 0.2 |
| ACE inhibitor | 7.3 | 6.1 | 5.5 | 5.0 | 2.9 | 3.5 | 3.5 |
| Aspirin/NSAIDs | 6.7 | 7.1 | 4.4 | 6.0 | 2.8 | 4.0 | 5.5 |
| Current smoker, % | 3.0 | 3.9 | 3.4 | 5.8 | 2.4 | 2.8 | 4.8 |
| Frontline healthcare worker, % | 5.6 | 13.4 | 10.1 | 7.1 | 6.4 | 14.1 | 5.1 |
| Contact with COVID-19 cases in community, % | | | | | | | |
| Suspected | 9.5 | 11.4 | 9.6 | 10.5 | 8.2 | 11.7 | 12.7 |
| Confirmed | 4.7 | 8.6 | 7.9 | 7.0 | 6.7 | 10.4 | 6.1 |

Abbreviations: ACE, angiotensin converting enzyme; IQR, interquartile range; NSAIDs, nonsteroidal anti-inflammatory drugs.

a Proportions are presented for categorical variables and were calculated based on the total number of participants with available data. Median (IQR) are presented for continuous variables.

technical occupations”, “farming, fishing, and forestry occupation”, and “transportation occupation”, among others, consistent with a report from the American Civil Liberties Union of Massachusetts [37].

2.5. Creation of the Neighborhood Deprivation Index in the US

Details about the Neighborhood Deprivation Index (NDI) have been described previously [23]. Briefly, based on a review of literature, we identified 25 census variables that have been used consistently to approximate neighborhood-level environments for possible inclusion in the deprivation index. We used principal component analysis (PCA) for census data reduction and retained the first principal component. Variables were then assessed for inclusion based on two a priori criteria: First, variables that had a loading above 0.25 were included in the index. Second, we stipulated that the lower 95% confidence limit of the variable loading could not be below 0.68, which was chosen because it was the lower 95% confidence limit for the median variable loading. Of the 25 variables included in the PCA, seven variables were retained for the index (Supplementary Table 2). Ordination was then repeated using only these census variables to obtain the final loadings. The NDI was standardized to have a mean of 0 and a standard deviation of 1 by dividing the index by the square of the eigenvalue.

2.6. Collection of Index of Multiple Deprivation in the UK

For the UK, we collected the Index of Multiple Deprivation (IMD) for each Lower Layer Super Output Area (LSOA) through the Office for National Statistics (England) [24], the Welsh Government (Wales) [25], the Scottish Government (Scotland) [26], and the Northern Ireland Statistics and Research Agency (Northern Ireland) [27]. We combined scores from each of the UK’s four constituent countries into a unified scale by assuming the same distribution of deprivation scores in each country. Individual components of the IMD include income, education, employment, barriers to housing and services, living environment, health, and crime (Supplementary Table 2). To provide consistency in the presentation of the directionality of deprivation between the NDI and the IMD, the order of the IMD scale was reversed such that the highest quintile in both the NDI and the IMD reflected the “most deprived” category.

2.7. Statistical analysis

We performed logistic regression analysis conditioned on age, sex, and date of study entry to estimate the odds ratios (ORs) and 95% confidence intervals (CIs) for testing positive for COVID-19 throughout follow-up according to race/ethnicity. Additional covariates included in the multivariable models were selected a priori as putative risk factors for COVID-19 and grouped into comorbidities, occupation as frontline healthcare worker (HCW), occupational risk factors, and personal contact with COVID-19 in the community. We applied inverse probability weighting (IPW). Each participant was weighted according to the inverse probability of receiving a test for COVID-19 calculated as a function of age, sex, date of study entry, race/ethnicity, symptoms, and occupation as frontline HCW. Because we previously found a higher risk of testing positive for COVID-19 in the healthcare setting [28], we also examined the race/ethnicity–COVID-19 relationship within frontline HCWs. Given the dynamic nature of the pandemic, we further performed an analysis stratified by time period (first wave [March 29–June 15, 2020], second wave
We hypothesized that, since personal contact with COVID-19 appeared to be a strong mediator of the risk of COVID-19 among racial minorities, community-level socioeconomic factors may mediate the association between race/ethnicity and risk of COVID-19. We examined the association between race/ethnicity, community-level socioeconomic factors, and risk of COVID-19 using univariate logistic regression analyses conditioned on age, sex, and date of study entry. Community-level socioeconomic factors were assessed through the NDI in the US and the IMD in the UK as well individual components of the NDI and the IMD.

Lastly, structural equation models were implemented to conduct a mediation analysis using the “lavaan” package in R. Potential mediators, from upstream to downstream, included community-level socioeconomic factors, personal contact with COVID-19, occupation, and comorbidities (Fig. 4). We computed the proportion of total effect that was explained by indirect effects of each of the mediators to estimate the relative contributions to the association between race/ethnicity and COVID-19.

We conducted all analyses using R 3.6.1 (Vienna, Austria). All statistical tests were two-sided with a P value less than 0.05 indicating statistical significance.

2.8. Role of funding source

The sponsors had no role in study design, analysis, and interpretation of data, report writing, and the decision to submit for publication.

3. Results

3.1. Study population

In the US, 210,961 participants identified as non-Hispanic White (herein described as White), 8,140 as non-Hispanic Black (Black), 19,277 as Hispanic/Latino (Hispanic), 11,596 as non-Hispanic Asian (Asian), and 8,814 as more than one/other race (Table 1). In the UK, 1,736,547 participants identified as White, 10,949 as Black, 37,638 as South Asian, 6,828 as Middle Eastern, 5,762 as Chinese, 1,713 as East/Southeast Asian, and 44,139 as more than one/other race (Table 2). The median age was 52 years (interquartile range [IQR] 35–66) in the US and 48 years (IQR 31–61) in the UK. In both countries, Black participants were more likely to have obesity, diabetes, and kidney disease compared to other participants. Racial minorities were also more likely to work as frontline HCWs and have personal contact with COVID-19 compared to White participants.

3.2. Risk of COVID-19 among US racial and ethnic minorities

In the US, compared to White participants, Black and Hispanic participants had an increased risk of reporting a positive COVID-19 test (age-adjusted OR [95% CI], 1.52 [1.36–1.71] for Black participants and 1.73 [1.62–1.85] for Hispanic participants) (Table 3). These ORs were not materially altered after additional adjustment for comorbidities and occupation as frontline HCW. In analyses restricted to HCWs, we observed similar increases in risk among Black and Hispanic HCWs compared to White HCWs. For the overall population, additional adjustment for contact in the community with a person with suspected or confirmed COVID-19 attenuated the risk estimates. Notably, in a stratified analysis, the increased risk of COVID-19 experienced by Black and Hispanic participants was more pronounced in the first wave, followed by the second wave in the US (Supplementary Table 3).

We hypothesized that, since personal contact with COVID-19 appeared to be a strong mediator of the risk of COVID-19 among racial minorities, community-level socioeconomic factors may mediate the association between race/ethnicity and risk of COVID-19. Overall, participants living in communities in the highest quintile of the NDI (most deprived) had an OR of 1.24 (95% CI, 1.20–1.28; P_trend < 0.001) for personal contact with COVID-19 and 1.71 (95% CI, 1.60–1.84; P_trend < 0.001) for testing positive for COVID-19 compared to those in the lowest quintile (least deprived) (Table 5).
Increased risk of reporting a positive COVID-19 test was observed among Black, South Asian, and Middle Eastern participants (age-adjusted ORs ranging from 1.25 to 1.88) (Table 4). As with the US participants, we found minimal attenuation of the risk estimates after accounting for comorbidities. Among frontline HCWs, we observed a similar increase in risk among South Asian participants. Additional adjustment for personal contact with COVID-19 attenuated the risk estimates for overall UK participants. Similar to the US, we observed greater racial/ethnic disparities in COVID-19 risk in the first wave compared to the second wave of the pandemic in the UK (Supplementary Table 4).

We assigned each UK app user an Index of Multiple Deprivation (IMD) [24]. Individual domains and their distribution across quintiles of the IMD are shown in Supplementary Table 2. Participants living in communities in the highest quintile of the IMD (most deprived; see Methods) had an OR of 1.11 (95% CI, 1.10–1.12; \( P_{\text{trend}} < 0.001 \)) for contact with someone with suspected or confirmed COVID-19 and 1.26 (95% CI, 1.22–1.29; \( P_{\text{trend}} < 0.001 \)) for testing positive for COVID-19 compared to the lowest quintile (least deprived) (Table 5). Each domain comprising the IMD except for housing was associated with an increased risk of personal contact with COVID-19 and testing positive for COVID-19 (Supplementary Fig. 2). Black participants, in particular, were more likely to live in socioeconomically deprived communities as defined by the IMD (OR, 3.00; 95% CI, 2.88–3.12) (Fig. 1) and individual IMD domains compared to White participants (Fig. 3).

In the UK, using a structural equation model, the proportion of increased COVID-19 risk compared to White participants mediated by community-level deprivation was higher in Black participants (18.2%) than in South Asian (4.0%) and Middle Eastern participants (4.3%) despite all three racial groups showing an excess risk of testing positive for COVID-19 (Table 6 and Fig. 4). Additionally, considering potential downstream mediators of community risk resulted in a remaining 7.7% of excess risk mediated by community-level deprivation in Black participants.

### 4. Discussion

Among over two million individuals, racial and ethnic minorities, particularly Black and Hispanic participants in the US and Black, South Asian, and Middle Eastern participants in the UK, experienced a greater risk of COVID-19 compared to White participants, especially during the first wave of the pandemic. These minority groups experienced a higher risk of living in more socioeconomically deprived communities; personal contact with COVID-19 in the community was a significant mediating factor for the association between race/ethnicity and COVID-19 risk. A substantial proportion of COVID-19 risk was mediated by community-level deprivation, especially for Black participants. Similar findings were observed in the US and the UK, providing evidence that country-specific social determinants of health observed among minority communities are likely significant risk factors for COVID-19.

These findings are consistent with prior studies of racial and ethnic disparities in COVID-19 risk. Prior studies using ecological data found attenuated associations between race/ethnicity and COVID-19 infection after adjusting for community-level factors [8,10,11]. However, these studies did not examine individual risk in the context of community-level impacts [12,13]. A recent study of 18,917 participants in the UK Biobank showed that ethnic minority background and community-level socioeconomic status assessed by the Townsend Deprivation Index are important COVID-19 risk factors among individuals with cancer [29]. Our analysis provides robust results that address this gap by concurrently examining personal exposure to COVID-19, occupation, and comorbid conditions, and community-level socioeconomic factors on a population scale using participant information not commonly available in registry or hospital-based cohorts. Our results demonstrate that comorbid conditions do not explain a substantial proportion of the increased likelihood of
COVID-19 infection among minority populations in the US and the UK. In contrast, contact in the community with individuals with COVID-19 played an important role in the differential risk of COVID-19 among racial/ethnic minorities, as shown by the attenuation of the race/ethnicity-COVID-19 association and the mediation analysis. An individual’s likelihood of contact with COVID-19 can be influenced by structural and individual factors. On the structural level, communities of color are highly represented among the essential workers in Black participants in the US and the UK, respectively. The role of genetics in the now established racial disparities in COVID-19 risk is controversial. Although some studies have demonstrated that the expression of the gene facilitating SARS-CoV-2 infection is greater among Black individuals compared to those of other races/ethnicities [32], so far there is little evidence to support the role of underlying genetics as a primary contributor to these observed differences. Race, as measured in this and other studies, is a social construct, self-defined by participants, that changes with time and between geographic locations, and has variable concordance with genetic ancestry [33]. Our results demonstrate increased COVID-19 risk across multiple racial/ethnic groups who are socially and economically marginalized to varying degrees yet are unlikely to share genetic variation in yet unidentified genes associated with COVID-19 risk.

### Table 4

| Race/ethnicity | White | Black | South Asian | Middle Eastern | Chinese | East/Southeast Asian | More than one/other race |
|----------------|-------|-------|-------------|----------------|---------|----------------------|------------------------|
| Overall participants\(^a\) | 39594 | 323 | 1247 | 229 | 113 | 51 | 1071 |
| No. of cases | 1736547 | 10949 | 37638 | 6828 | 5762 | 1713 | 44139 |
| Age-adj OR (95% CI)\(^b\) | 1.0 (reference) | 1.0 (reference) | 1.0 (reference) | 1.0 (reference) | 1.0 (reference) | 1.0 (reference) | 1.0 (reference) |
| Comorbidity-adj OR (95% CI)\(^c\) | 1.24 (1.11-1.39) | 1.25 (1.12-1.39) | 1.25 (1.12-1.39) | 1.39 (1.30-1.49) | 1.39 (1.30-1.49) | 1.39 (1.30-1.49) | 1.39 (1.30-1.49) |
| Comorbidity + occupation-adj OR (95% CI)\(^d\) | 1.57 (1.47-1.68) | 1.57 (1.47-1.68) | 1.57 (1.47-1.68) | 1.68 (1.59-1.79) | 1.68 (1.59-1.79) | 1.68 (1.59-1.79) | 1.68 (1.59-1.79) |
| Comorbidity + occupation + personal contact with COVID-19-adj OR (95% CI)\(^e\) | 1.0 (reference) | 1.0 (reference) | 1.0 (reference) | 1.0 (reference) | 1.0 (reference) | 1.0 (reference) | 1.0 (reference) |

### Abbreviation:
- adj: adjusted; CI: confidence interval; OR: odds ratio.
- \(^a\) All models were weighted according to the inverse probability of testing for COVID-19 calculated as a function of age, sex, date of study entry, race/ethnicity, symptoms (fatigue, headache, sore throat, chest pain, shortness of breath, persistent cough, diarrhea, abdominal pain, skipped meals/anorexia, hoarse voice, myalgias, delirium, loss of smell/taste, fever), and occupation as frontline healthcare worker (among overall participants).
- \(^b\) Logistic regression model conditioned on age, sex, and date of study entry.
- \(^c\) Additionally adjusted for body mass index (17-18.4, 18.5-24.9, 25-29.9, and \(\geq 30\) kg/m\(^2\)), history of diabetes (no, yes), heart disease (no, yes), lung disease or asthma (no, yes), kidney disease (no, yes), cancer (active or in the past; no, yes), and smoking status (never/former smokers, current smokers).
- \(^d\) Additionally adjusted for occupation as frontline healthcare worker (no, yes; among overall participants). For healthcare workers, the model was additionally adjusted for access to personal protective equipment (reuse or inadequate, adequate) and practice setting (inpatient, nursing homes, outpatient hospital clinics, home health sites, ambulatory clinics, other).
- \(^e\) Additionally adjusted for personal contact with COVID-19 (no, suspected COVID-19, confirmed COVID-19).
Our study has several strengths. The bi-national data from a common survey instrument provided a unique opportunity to compare findings in racial/ethnic minority groups with shared ancestry yet disparate social, economic, and cultural experiences. Notably, racial and ethnic disparities in COVID-19 risk exist in both countries despite social and policy differences between the two areas, such as a universal healthcare system in the UK versus the hybrid private and public healthcare system in the US. Other strengths include examining COVID-19 in a population-wide sample, overcoming limitations related to capturing only more severe cases through hospitalization records or death reports; accounting for a wide range of personal risk factors for COVID-19 generally not available at a population scale.

Fig. 2. Risk of living in community with specific measures of deprivation according to race and ethnicity in the United States. Data points represent the odds ratios with 95% confidence intervals. White participants were used as the reference group. “Hispanic” was defined as any race of Hispanic or Latino ancestry, while other racial categories were defined as each respective race not of Hispanic or Latino ancestry. Census data from the US Census Bureau were assigned to each participant based on ZIP Code Tabulation Areas. Each domain categorized based on these cutoffs was associated with an increased risk of personal contact with COVID-19 and testing positive for COVID-19 in Supplementary Fig. 1.
and accounting for community-level sociodemographic variables for each participant.

We acknowledge several limitations. While the use of syndromic surveillance to better understand the COVID-19 pandemic has great strengths in flexibility, speed, and sample size, this methodology is dependent upon self-reported data, which is susceptible to measurement error, and voluntary participation, which is prone to selection (collider) bias [34,35]. Racial and ethnic minority groups and those who are older, have lower income, or have lower health literacy may be less likely to participate in a smartphone-based study [36]. Although the proportion of racial and ethnic minority participants in our study was lower than national demographics, we were still able to enroll a considerable number of participants from these underrepresented groups [18]. In addition, given the nature of the study, we recruited primarily individuals from different racial and ethnic minority groups with similar levels of access to technology. This may minimize differences in community-level socioeconomic factors observed in the general population, which would tend to underestimate broader racial and ethnic disparities in COVID-19 risk compared to population samples that do not incorporate voluntary participation through a common data collection instrument. In fact, the use of a smartphone application for data collection allowed us to demonstrate racial and ethnic disparities that persisted despite uniform access to technology. Although it is possible that symptomatic or high-risk individuals may be more likely to participate, it is unlikely that this difference would vary by race or ethnicity. Furthermore, our findings from the mediation analysis should be interpreted with caution due to the potential for unmeasured individual-level variables that might correlate with community-level factors. We used community-level data to estimate socioeconomic factors which may not capture more specific structural inequities experienced by a participant. However, assessing sensitive personal data on such a large scale would not have been feasible. Finally, the exclusion of participants who declined to provide data on race and ethnicity might fail to account for a severely underrepresented population, potentially biasing results towards the null.

In conclusion, within a large population-wide sample of individuals in the US and the UK, we demonstrate a significantly increased risk of COVID-19 in certain racial and ethnic minority groups compared to White individuals, which appeared to be mediated in part by community-level socioeconomic factors, especially in Black individuals. Our findings stress the importance of allocating resources to specific communities and the need to build robust public health infrastructure accessible to all.

**Data sharing statement**

Data collected in the app are being shared with other health researchers through the NHS-funded Health Data Research UK (HDRUK)/SAIL consortium, housed in the UK Secure e-Research Platform (UKSeRP) in Swansea. Anonymized data collected by the COVID Symptom Study app can be shared with bona fide researchers via HDRUK, provided the request is made according to their protocols and is in the public interest (see [https://healthdatagateway.org/detail/9b604483-9cdc-41b2-b82c-14ee3dd705f6](https://healthdatagateway.org/detail/9b604483-9cdc-41b2-b82c-14ee3dd705f6)). US investigators are encouraged to coordinate data requests through the COPE Consortium ([www.monganinstitute.org/cope-consortium](http://www.monganinstitute.org/cope-consortium)). Data updates can be found at [https://covid.joinzoe.com](https://covid.joinzoe.com).

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| United States | Personal contact with COVID-19 | COVID-19 infection |
|---------------|------------------------------|--------------------|
|                | No. of cases | OR (95% CI)  | No. of cases | OR (95% CI) |
| Quintile 1 (least deprived) | 6721 | 1 (reference) | 1281 | 1 (reference) |
| Quintile 2 | 6732 | 1.01 (0.97-1.04) | 1556 | 1.20 (1.12-1.30) |
| Quintile 3 | 7199 | 1.07 (1.03-1.10) | 1810 | 1.36 (1.26-1.46) |
| Quintile 4 | 7977 | 1.14 (1.10-1.17) | 2056 | 1.46 (1.36-1.57) |
| Quintile 5 (most deprived) | 9356 | 1.24 (1.20-1.28) | 2654 | 1.71 (1.60-1.84) |
| **P<sub>rend</sub>** | <0.001 | <0.001 |

| United Kingdom | Personal contact with COVID-19 | COVID-19 infection |
|----------------|------------------------------|--------------------|
|                | No. of cases | OR (95% CI)  | No. of cases | OR (95% CI) |
| Quintile 1 (least deprived) | 52716 | 1 (reference) | 8274 | 1 (reference) |
| Quintile 2 | 50106 | 1.04 (1.03-1.05) | 7560 | 1.05 (1.01-1.08) |
| Quintile 3 | 52831 | 1.04 (1.02-1.05) | 8582 | 1.04 (1.01-1.07) |
| Quintile 4 | 53159 | 1.06 (1.05-1.08) | 8437 | 1.09 (1.05-1.12) |
| Quintile 5 (most deprived) | 56063 | 1.11 (1.10-1.12) | 9775 | 1.26 (1.22-1.29) |
| **P<sub>rend</sub>** | <0.001 | <0.001 |

Abbreviations: CI, confidence interval; OR, odds ratio.

- *Community-level deprivation was represented by the Neighborhood Deprivation Index in the United States and the Index of Multiple Deprivation in the United Kingdom. Higher scores represented more deprived neighborhood.*
- *Logistic regression model adjusted for age, sex, and date of study entry.*
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**Declaration of Competing Interest**

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.eclinm.2021.101029.

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